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TEMPERATURE AND AQUATIC LIFE

Federal Water Pollution Control Administration
Cincinnati, Ohio

December 1967

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TEMPERATURE AND AQUATIC LIFE

LABORATORY
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TECHNICAL ADVISORY AND INVESTIGATIONS BRANCH

FEDERAL WATER POLLUTION CONTROL ADMINISTRATION

UNITED STATES DEPARTMENT OF THE INTERIOR

5555 Ridge Avenue

Cincinnati, Ohio 45213

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FOREWORD

The Laboratory Investigations series was initiated by the Technical Advisory and Investigations Branch in 1963. The series was planned to describe laboratory methods and techniques and to disseminate information that may be of interest and use to other activities of FWPCA.

The current addition to the series is a literature review of the effects of thermal pollution on the aquatic ecosystem. Thermal pollution is a rapidly increasing problem and this review will aid in evaluating existing problems and in the prevention of future problems.

December 1967

TEMPERATURE AND AQUATIC LIFE

Laboratory Investigations - Number 6

Technical Advisory and Investigations Branch
Technical Services Program
Federal Water Pollution Control Administration
United States Department of the Interior
Cincinnati, Ohio

December 1967

1a

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INTRODUCTION

Temperature, a catalyst, a depressant, an activator, a restrictor, a stimulator, a controller, a killer, is one of the most important and most influential water quality characteristics to life in water. Temperature determines those species that may be present; it activates the hatching of young, regulates their activity and stimulates or suppresses their growth and development; it attracts, and kills when the water becomes too hot or becomes chilled too suddenly. Colder water generally suppresses development; warmer water generally accelerates activity and may be a primary cause of aquatic plant nuisances when other environmental factors are suitable.

Because of the importance of this single environmental facet to aquatic ecology, this report was developed to consider some of the features of temperature and its interrelationships. It is divided into five segments; these are:

I. Chemical Reactions
II. Bacteria
III. Freshwater Fishes
IV. Marine, Estuarine and Anadromous Fishes
V. Aquatic Plants and Benthos

An extensive temperature bibliography is appended.

SUMMARY

1. Chemical reaction rates vary with temperature, generally increasing as the temperature is increased.
2. The solubility of gases in water varies with temperature. Dissolved oxygen is decreased by the decay or decomposition of dissolved organic substances; the decay rate increases as the temperature of the water increases reaching a maximum at about 30°C (86°F).
3. The temperature of stream water, even during the summer, is below the optimum for pollution-associated bacteria. Increasing the water temperature increases the bacterial multiplication rate when the environment is favorable, and the food supply is abundant. Increasing the water temperature within the growth range of the bacteria causes a more rapid die-off when the food supply is limiting.
4. Warm water fish can survive temporarily in waters heated artificially to 33.9°C (93°F); some fish populations, such as roach, perch, and carp, are reduced at these high temperatures. In cold weather, stream temperatures should be substantially below 33.9°C (93°F) to prevent mortalities when fish move through excessive temperature gradients. Cold water non-anadromous fish populations such as trout should not be subjected to temperatures exceeding 14.5°C (58°F). In cold weather stream temperatures should be below 14.5°C (58°F) to prevent mortalities of cold water fishes.

5. Sudden changes in temperature can be more harmful to some species of fish than continued exposure to a higher temperature.
6. Fish can adapt to higher temperatures faster than to lower temperatures.
7. The maximum temperature for a given species of fish varies with the fish's rate of heating, size, and physiological condition.
8. Fish may starve at elevated temperatures because of their inability to capture food.
9. Fish seek out a preferred temperature at which they can best survive, which is several degrees below their lethal temperature.
10. The toxic effects to fish of certain material increase with temperature.
11. Temperature changes are most important to fish in enclosed areas in the marine environment such as estuaries and bays as opposed to open areas although tolerance to temperature fluctuations is greater in fresh-water and estuarine forms than in open water marine species.
12. There are restricted ranges of temperature within which fish can reproduce successfully; larval development especially requires narrow ranges of temperature. A fish population may exist in a heated area only by continued immigration from the outside. Fish may be absent from such areas during warm summer months and present in cold winter months.
13. Increased temperatures may block the migrations of anadromous fish.
14. Cold is as important to fish populations as heat because of the inability of fish to acclimate quickly to rapid decreases in temperature. Thus, in some areas fish populations may be limited by decreases as well as

increases in temperature. The growth rate of fishes is reduced in waters colder than the optimum temperature range for the species.

15. When water temperatures increase, the predominate algal species change from diatom to green algae and finally at high temperatures to blue-green algae.

16. The number and distribution of bottom organisms decrease as water temperatures increase above 90°F, which is close to the tolerance limit for a "balanced" population. The adult stage of many species is able to tolerate higher temperatures than the eggs or young.

17. A benefit of heated effluents is the defouling of intake pipes accomplished by reversing the flow of water through the pipes.

18. Certain benefits, including open water winter fishing in otherwise ice covered areas, and a cold water fisheries downstream from deep reservoirs, can be derived from artificially induced temperature changes. The benefits of fish being attracted to heated water in the winter months may be negligible compared to fish mortalities that may result when the fish return to the cooler water; lethal temperatures may result from heated discharges in the summer months.

I. CHEMICAL REACTIONS

Introduction

All the impurities contained in a water result from intimate contact of the water with such impurities during which a portion are dissolved or suspended. The process of solution is a chemical reaction which proceeds as long as the water is in contact with a soluble substance or until equilibrium is reached (Camp, 1963). In general the solubility of solids and liquids may be considered a function of temperature, unless extreme pressure conditions are involved.

The solubility of nonreactive gases (gases that do not react with water to an appreciable extent) at equilibrium with the atmosphere is proportional to the partial pressure of the gas in the atmosphere and follows Henry's law, $Cs=KsP$, where Cs is the saturation concentration of the gas in the water, P is the partial pressure of the gas phase and Ks is the proportionality constant called the coefficient of absorption. Water is saturated with a gas when the proportionality implied in Henry's law is fully established. Rising temperatures decrease the saturation value as do the salts of hard and brackish waters (Fair and Geyer, 1954). The solubility of reactive gases in water is modified because they ionize in and/or react with the water.

The establishment of equilibrium in a given chemical reaction implies that the reaction is reversible and that a point has been reached where a balance between the reactants exists. Mathematically, this relation is expressed by the mass action law

$$mA+nB+\cdots \rightleftarrows pC+qD+\cdots$$

where capital letters refer to types of molecules or ions taking part in the reaction and lower case letters to the number of them. On the basis of thermodynamic principles the relation

$$\frac{(C)^p(D)^q}{(A)^m(B)^n}=k$$

is universally true, the parentheses indicating activities of the enclosed substances. The equilibrium constant k has a characteristic value for each reaction that is dependent only on temperature (Fair and Geyer, 1954).

The effects of temperature on equilibria are given by the Van't Hoff equation $\frac{d(\log_e K)}{dT}=\frac{\Delta H_f^\circ}{RT^2}$

where K is the equilibrium constant, T is the Kelvin temperature, R is the gas constant, ΔH_f° is the enthalpy change per gram-molecular weight for the reaction from left to right. Integration of the above equation between the limits T_1 and T_2 gives

$$\mathrm{Log}_e\frac{K_2}{K_1}=\frac{\Delta H_f^\circ}{RT_1}-\frac{\Delta H_f^\circ}{RT_2}=\frac{\Delta H_f^\circ(T_2-T_1)}{RT_1T_2}$$

for constant ΔH_f^{o} and conversion to common logarithms

$$\mathrm{Log}\frac{K2}{K_1} = -\frac{\Delta H_f^{o}}{2.303R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = \frac{\Delta H_f^{o}}{4.576}\left(\frac{T_2 - T_1}{T_1T_2}\right)$$

(Glasstone and Lewis, 1960).

The rates of most chemical reactions increase as the temperature is raised. A frequently used very approximate rule, enunciated by Van't Hoff, is that the rate doubles for each rise in temperature of 10°C (18°F).

Mathematically, the change in specific rate constant with temperature for any simple chemical reaction is given by the Arrhenius equation $\frac{d(\log_e k)}{dt} = \frac{E}{(RT^2)}$

where k is the specific reaction rate constant, T is the Kelvin temperature, R is the gas constant (1.99 cal/degree C), E is a constant characteristic of the reaction and termed the activation energy. Integration of the above equation between the limits T_1 and T_2 gives

$$\mathrm{Log}_e\frac{k2}{k1} = \frac{E}{RT_1} - \frac{E}{RT_2} = \frac{E(T_2 - T_1)}{RT_1T_2}$$

for constant E and conversion to common logarthms

$$\mathrm{Log}\frac{k2}{k_1} = \frac{-E}{2.303R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) = \frac{E}{4.576}\left(\frac{T_2 - T_1}{T_1T_2}\right)$$

(Glasstone and Lewis, 1960).

Two other methods for expressing the temperature dependence of a reaction rate are often encountered. They are:

$$\frac{k_2}{k_1} = \Theta^{T_2 - T_1}$$

whence

$$\Theta = \frac{k_2}{k_1} \text{ for } T_2 - T_1 \quad \text{and} \quad Q_{10} = \frac{k_2}{k_1} \text{ for } T_2$$

here T_2 and T_1 are measured in degrees centigrade (Fair and Geyer, 1954).

Dissolved Gases

1. Non-Reactive Gases

The gases that do not react to an appreciable extent with water but which occur in sufficient quantities to be determined by chemical analyses are oxygen, nitrogen, hydrogen and methane.

Oxygen

Since all living organisms are dependent on oxygen in one form or another to maintain the metabolic processes that produce energy for growth and reproduction, it is of great significance in the aquatic environment. The solubility of atmospheric oxygen (see Figure 1) in fresh waters ranges from 14.6 mg/l at 0°C (32°F) to 6.6 mg/l at 40°C (104°F) under 1 ATM of pressure (Anon., 1965). It is a poorly soluble gas and its solubility varies directly with the atmospheric pressure at any given temperature as expressed in Henry's law.

Oxygen solubility is affected also by the presence of dissolved salts as in hard and brackish waters. In brackish waters containing 5,000 mg/l of chloride, the solubility of atmospheric oxygen varies from 13.8 mg/l at 0°C (32°F) to 7.3 mg/l at 30°C (86°F) under 1 ATM of pressure (Anon., 1965).

In thermally stratified lakes, the hypolimnion may have a low oxygen content during summer stagnation because of its use in decomposition of organic matter. In addition, stratification may occur in streams when heated effluents are discharged. There are three recognized stream stratification forms: overflow, interflow, and underflow; the form being determined by the relationship between the density of the effluent and the density of the stream flow (Dysart and Krienkel, 1965). The principal source of dissolved oxygen is the air; oxygen

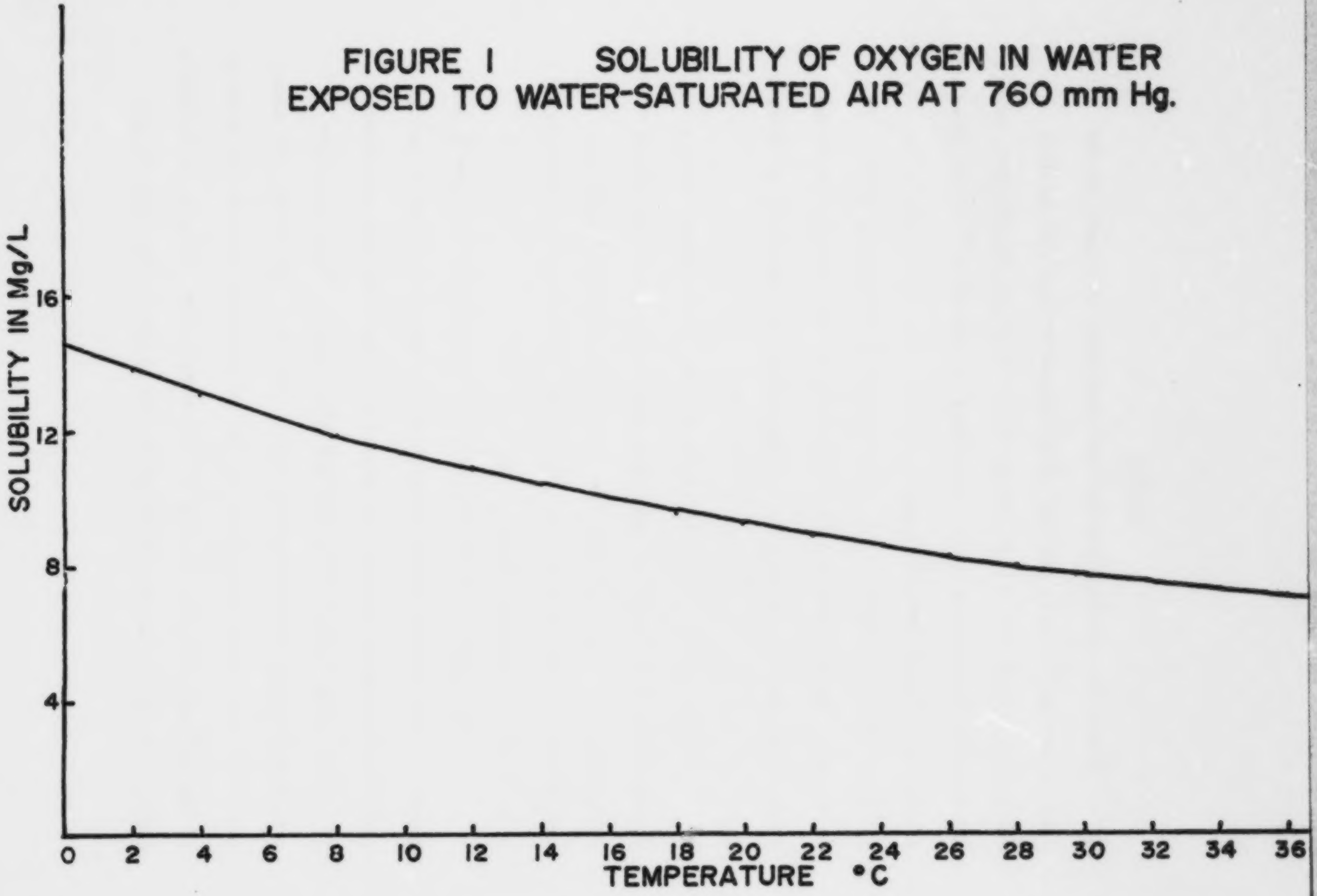

FIGURE 1 SOLUBILITY OF OXYGEN IN WATER EXPOSED TO WATER-SATURATED AIR AT 760 mm Hg.

is also produced by chlorophyll-bearing algae and submerged aquatic plants through photosynthesis.

In natural waters deficient in dissolved oxygen, accelerated atmospheric aeration (reaeration) is evident. The rate of reaeration in each unit of time is proportional to the remaining degree of unsaturation of dissolved oxygen in the waters (Streeter, 1958). Temperature influences the rate of solution and affects the rate of diffusion of oxygen. As temperature increases the saturation capacity declines and the rate of diffusion increases (Velz and Gannon, 1960).

Nitrogen

The solubility of atmospheric nitrogen in water is about one-half that of oxygen. While the principal source of nitrogen is the air, denitrifying bacteria will release nitrogen to water (Allee et al., 1949). In a lake the waters of the hypolimnion become and remain supersaturated with nitrogen as they get warmer; rapid warming may cause nitrogen to escape as bubbles (Nordell, 1961).

Methane

Methane is not a permanent constituent of the earth's atmosphere (Camp, 1963). The primary source of methane in natural waters is anaerobic decomposition. Solubility of methane varies from 39.6 mg/l at 0°C (32°F) to 15.9 mg/l at 40°C (104°F) and 760 mm of mercury

(Nordell, 1961). Some ground waters may contain sufficient methane to constitute a fire and explosion hazard. Methane may persist even after aeration.

Hydrogen

The solubility of hydrogen varies from 1.93 mg/l at 0°C (32°F) to 1.48 mg/l at 40°C (104°F) in pure water in contact with the pure gas at 760 mm of mercury (Nordell, 1961). Hydrogen comprises less than 0.001% of the earth's atmosphere (Camp, 1963). It is produced in the water primarily from anaerobic decomposition of organic matter.

Dissolved Organic Substances

Organic substances in surface waters decay or decompose chiefly by bacterial action and exert a demand on the dissolved oxygen of such waters. This biochemical reaction is similar to an unimolecular chemical reaction, that is, the rate is approximately proportional to the remaining concentration of unoxidized organic matter. Thus the biochemical oxygen demand of a surface water is a measure of the concentration of decomposable organic matter (Camp, 1963). The reaction rate ordinarily expressed as k rises as the temperature of the water increases reaching a maximum at about 30°C (86°F), (Hoak, 1961). This increased rate results in a greater demand on the dissolved oxygen in the surface water. Theriault (1927) has shown that at 20°C (68°F) the biological oxidizability of polluted water increases by about 2% for each degree centigrade increase.

2. Reactive Gases

Gases that react with water are hydrogen sulfide, carbon dioxide, sulfur dioxide and ammonia. These either ionize in water or react with the water to produce ions.

Hydrogen Sulfide

The principal sources of hydrogen sulfide in natural waters are anaerobic decomposition of organic matter and the discharge of industrial wastes from oil refineries, leather tanneries, chemical plants and paper mills (Camp, 1963); the solubility of hydrogen sulfide ranges from 7,070 mg/l at 0°C (32°F) to 2,360 mg/l at 40°C (104°F) and 760 mm of mercury (Nordell, 1961). It ionizes in water in two steps--

1. $H_2S \rightleftharpoons H^+ + HS^-$
2. $HS^- \rightleftharpoons H^+ + S^=$

An equilibrium relation is established for each step as follows:

1. $\frac{[H^+][HS^-]}{[H_2S]}$
2. $\frac{[H^+][S^=]}{[HS^-]}$

with equilibrium constants of 1.1×10^{-7} at 25°C (77°F) for step 1 and 1×10^{-14} at 25°C (77°F) for step 2. Equilibrium constants vary with temperature and corresponding values at 18°C (64.4°F) are 5.7×10^{-8} and 1.2×10^{-15} (Lange, 1961). As indicated by the comparative magnitude of the equilibrium constants for hydrogen sulfide at 25°C (77°F) the equilibrium in step 1 lies to the side of the product, i.e. H^+ and HS^-, while the equilibrium in step 2 lies to the side of the reactant, i.e. HS^-. Because the equilibrium constants for steps 1 and 2 at 18°C (64.4°F) are less than the corresponding values at 25°C (77°F) it follows that reactions 1 and 2 decrease with a decrease in temperature (Prutton, 1951).

Sludge deposits in streams and estuaries produce hydrogen sulfide as they undergo anaerobic decomposition in which sulfates are reduced. Wheatland (1954) has indicated that the rate of formation of sulfide increases with temperature, doubling approximately for each 10°C (18°F) rise, and that reduction of sulfate to sulfide will occur at temperatures as low as 5°C (41°F); but even at 25°C (77°F) is inhibited by traces of dissolved oxygen. Hydrogen sulfide is oxidized in the presence of dissolved oxygen to water and free sulfur or to sulfate.

Carbon Dioxide

Free carbon dioxide is found in most surface waters and may range from 0 to 5 mg/l in rivers. Lake waters may contain from 0 to 2 mg/l at the surface with significant increases as the depth increases because of the processes of decay at or near the bottom (Allee, et al., 1949). Since the oxidation of organic matter furnishes carbon dioxide, much higher concentrations may be found in surface waters receiving organic wastes. Surface waters receiving acid mine drainage may show a high content of carbon dioxide; ground waters contain appreciable amounts of free carbon dioxide, ranging from 1 mg/l to several hundred (Nordell, 1961).

The solubility of pure carbon dioxide in water ranges from 3,350 mg/l at 0°C (32°F) to 970 mg/l at 40°C (104°F) and 760 mm of mercury (Nordell, 1961). The average carbon dioxide content of the air varies from 0.035 percent in the country to 0.06 percent in the cities and the solubility of atmospheric carbon dioxide in water ranges from 1.0 mg/l at 0°C (32°F) and 0.03 percent to 2.0 mg/l at 0°C (32°F) and 0.06 percent. At 40°C (104°F) the solubility is 0.3 mg/l and 0.6 mg/l respectively at 760 mm of mercury (Nordell, 1961). These values indicate that the carbon dioxide contributed to natural surface waters and ground waters from the atmosphere is negligible compared with that from decaying organic matter.

Carbon dioxide reacts with water to form a weakly dissociated acid-carbonic acid, $CO_2+H_2O \rightleftarrows H_2CO_3$

Carbonic acid is a dibasic acid ionizing in two steps:

1. $H_2CO_3 \rightleftarrows H^+ + HCO_3^-$
2. $HCO_3^- \rightleftarrows H^+ + CO_3^=$

An equilibrium relation is established for each step as follows:

1. $\frac{[H^+][HCO_3^-]}{[H_2CO_3]}$
2. $\frac{[H^+][CO_3^=]}{[HCO_3^-]}$

Equilibrium constant values for steps 1 and 2 respectively, are 4.31×10^{-7} and 5.6×10^{-11} at 25°C (77°F) (Lange, 1961). At this point carbon dioxide establishes an equilibrium relation with the mineral content of the water.

Ammonia

Ammonia is an intermediate product in the bacterial decomposition of nitrogenous organic matter and may be discharged to natural waters as a waste product of industry. The presence of free ammonia in natural waters is indicative of recent organic pollution, since the atmosphere is substantially free of this substance (Camp, 1963).

The gas reacts with water to produce ammonium hydroxide (often termed aqueous ammonia); the ammonium hydroxide in turn ionizes to produce ammonium and hydroxal ions.

$$NH_3+H_2O \rightleftarrows NH_4^+ + OH^-$$

An equilibrium relation is established as follows:

$$\frac{[NH_4^+][OH^-]}{[NH_4OH]}$$

With ionization constant values of 1.8×10^{-5} at 25°C (77°F) and 2.0×10^{-5} at 40°C (104°F) (Lange, 1961). The equilibrium is shifted toward the product side, i.e. NH_4^+; OH^- at higher temperatures. Because the hydroxyl ion is a product of the ionization of ammonium hydroxide, the degree of ionization can be related to the hydrogen ion concentration or pH. Camp (1963) indicates that 99.99% of the ammonia in dilute solutions at 25°C (77°F) is in the form of ammonium ion at a pH of 5 while at pH 11 only 1.78% is in this form.

Sulfur Dioxide

Sulfur dioxide is formed in one of three ways: (1) as an intermediate product in the oxidation of hydrogen sulfide under aerobic conditions, (2) in the reduction of sulfate under anaerobic conditions and (3) in the combination of elemental sulfur and oxygen. This is part of the sulfur cycle taking place in many natural waters (Sawyer, 1960). Combustion fumes from industrial operations may contribute to the sulfur dioxide content of natural waters.

Sulfur dioxide reacts with water to form sulfurous acid; the acid then ionizing in two steps--

1. $SO_2+H_2O \rightleftarrows H^++HSO_3^-$

2. $HSO_3^- \rightleftarrows H^++SO_3^=$

and equilibrium relation is established as follows:

1. $\dfrac{[H^+][HSO_3^=]}{[H_2SO_3]}$

2. $\dfrac{[H^+][SO_3^=]}{[HSO_3^-]}$

With ionization constant values of 1.72×10^{-2} and 6.24×10^{-8} at 25°C (77°F) for steps 1 and 2, respectively (Lange, 1961). In the presence of dissolved oxygen, sulfurous acid and the hydrogen sulfite ion are readily oxidized. The solubility of sulfur dioxide markedly decreases with increasing temperatures (Camp, 1963).

Dissolved Minerals

About 99% of the dissolved mineral matter found in natural waters embrace only 10 elements, namely; hydrogen, oxygen, sodium, potassium magnesium, calcium, silicon, sulfur, carbon and chlorine. These occur as ions, radicals or molecules. At ordinary temperatures of natural waters some complexing of major dissolved species may occur but is limited to the formation of ion pairs [e.g., $Na(CO_3)_2^{\equiv}$, $Na_2CO_3^{\circ}$] (Garrels and Christ, 1965). Helgeson (1964) in a study of the effects of elevated temperatures on the dissociation of complex ions in solution indicated that little or no changes occur unless there is an appreciable change in the density of the solution; with increasing temperature and decreasing density complexing is expected to increase.

At present only enough chemical information is available to permit calculation of the inter-actions that take place among the major dissolved species at earth surface temperatures in media as concentrated as sea water. The results of such calculations indicate that more than 30% of the sulfate and bicarbonate are tied up as ion pairs with cations, whereas 90% of the total carbonate is complexed. One-hundred percent of the chloride is present in the ionic form. Changes in temperature, pressure and composition of the water will modify this distribution; however, variations in temperature and pressure to which ocean waters are subjected will produce little change in distribution.

The effects of small variations in temperature [5°C(41°F) to 40°C(104°F)] on equilibria and reaction rates involving minor constituents in natural waters can not be determined at this time because of a lack of information on equilibrium constants, enthalpy changes and activation energies (Garrels and Christ, 1965).

Summary

1. Chemical reaction rates vary with temperature, generally increasing as the temperature is increased. The change in the specific rate constant is given by the Arrhenius equation.

2. The solubility of gases in water varies with temperature. Dissolved oxygen content of a surface water is decreased by the decay or decomposition of dissolved organic substances; the decay rate increases as the temperature of the water increases reaching a maximum at about 30°C (86°F).

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II. BACTERIA

Introduction

Temperature changes in the aquatic environment affect ecological relationships among the biota, processes of natural purification, and growth and survival of microorganisms. There are a wide variety of microorganisms found in the aquatic environment. The numbers and species in the population vary depending on whether they are in ground water, lakes, or streams. Unpolluted water bodies have low concentrations of microorganisms. The microbial content of natural waters is approximately proportional to the amount of organic matter present. Unpolluted waters usually have a greater number of species in proportion to their total population; conversely polluted waters usually have a greater total population in proportion to the number of bacterial species in their environment.

Many stream bacteria come from the air and soil. Bacteria in the air are aersols or suspended on dust particles that settle or fall with precipitation. Soil flora in water are due to precipitation and seeping ground water that becomes surface run-off when entering or forming a stream. Many of the microorganisms that are native to natural waters are especially adapted to the stream environment, and some are difficult or now impossible to grow on culture media.

Interest in the microbiology of water centers on the transmission of disease via the water route. Polluted waters have high concentrations of microorganisms from municipal or industrial waste waters. When a stream is polluted with the excreta of warm blooded animals, it is most likely to contain enteric pathogens. Indicator organisms (coliforms) are used to measure bacterial concentrations and indicate the potential presence of pathogens from sewage.

Industrial wastes add organic and inorganic materials to water and in some cases large numbers of bacteria, but, in general, they do not contain pathogenic organisms. Industrial wastes may be growth stimulating or toxic to bacteria (Heukelekian, 1953).

Water, an essential for all forms of life, can serve as a medium for growth and reproduction for many microorganisms. Environmental factors affecting the growth of microorganisms are chemical, physical, and nutritional. Although these factors are interdependent, the physical factor of temperature is one of the most important.

The relations of temperature to the growth of microorganisms are complex Some hardy bacteria grow in a wide temperature range; other fragile bacteria grow in a narrow temperature range. For each organism there is a minimum, the lowest temperature at which growth can occur; an optimum, the temperature most favorable for growth; and a maximum, the highest temperature at which growth and multiplication can occur.

Bacteria may be classified according to their temperature requirements for growth. Organisms having optimum growth temperatures under 20°C (68°F) are grouped as psychrophiles or cold-loving; these occur in the soil and cold waters of the north. Thermophiles, heat-loving organisms having optimum temperatures of 55° to 65°C (131 to 149°F) are found in soil, decaying organic matter, hot spring water and near the discharge points of hot water effluents. They are of little importance in stream ecology. The majority of bacteria are called mesophiles; they are the intermediate group, having optimum temperatures in the range between the extremes. Many of the organisms found in natural waters and soils are saprophytes (organisms that live on decaying organic matter); they have optimum temperatures of 22° to 28°C (70 to 82°F) and belong to the mesophilic group.

The parasitic bacteria have optimum temperatures of 37°C (98.6°F) and include those microorganisms pathogenic to man. Temperature changes greatly affect the rate of activity of these organisms.

The effect of temperature on the species of organisms cannot always be considered separately from the other environmental factors. Some species can be more abundant in the winter. others in the summer. when their environmental conditions are varied (Burrows, 1959).

Microbiotic Cycles

The interrelationships among aquatic biota are of primary importance to the aquatic environment (Ingram. Mackenthun. and Bartsch. 1966). In unpolluted waters, autotrophic algae and chlorophyll bearing bacteria initiate microbiotic cycles (Silvey and Roach, 1964). The metabolites and decomposition products of the organisms provide nutrients for use by gram-negative heterotrophic bacteria. The principal gram-negative organisms are Alcaligenes, Aerobacter, and Pseudomonas. In waters polluted with sewage, the Escherichia also increase, as do associated types. The new algal growth following the gram-negative bacilli may be either diatoms or blue-green algae. In cool waters the diatoms will generally prevail and be followed in turn by the gram-positive heterotophic bacilli. In warmer waters, the gram-negative bacilli remain and grow in coexistence with blue-green algae; then the actinomycetes grow and develop an antibiotic effect. reducing the gram-negative population. The gram-positive spore-forming bacilli follow the actinomycetes (Figure 2).

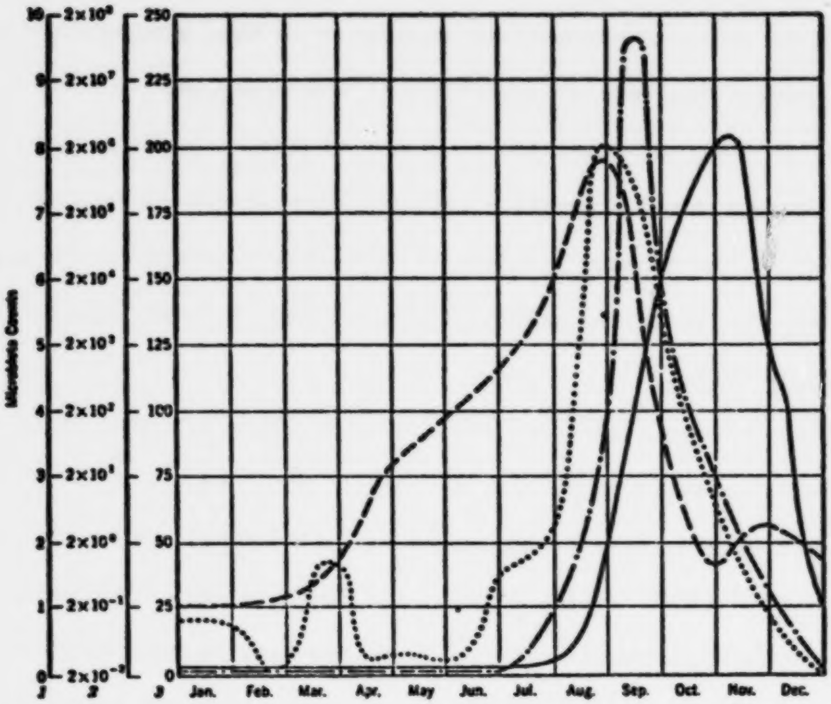

Fig. 2. Annual Cycles of Gram-Positive and Gram-Negative Heterotrophic Bacilli and Their Relationship to Blue-Green Algae and Aquatic Actinomycetes

The dotted curve is for blue-green algae, indicated in 100's of areal standard units on Scale 1 at the left; the solid curve is for gram-positive heterotrophs; the dashed curve, gram-negative heterotrophs; and the dot-and-dash curve, actinomycetes. Colony counts of heterotrophs are indicated in 1,000's by Scale 1; absolute numbers of bacilli by Scale 2; and actinomycete plate counts in 1,000's by Scale 3. Actinomycetes were isolated on M_1B_2 agar. Gram-positive heterotrophs were grown on vitamin-enriched Emerson's agar, and gram-negative heterotrophs on eosin methylene blue agar.

(From Silvey and Roach, 1964, p. 54)

These various cycles may impinge upon each other when the stream or reservoir is highly polluted.

Self-Purification

When organic wastes are discharged into a receiving water a complex chain of physical, chemical, biochemical and biological activities are started which result in decomposition and degradation of the wastes. This complex process is self-purification, the details of which are still unknown (Heukelekian, 1953).

The most significant function in natural purification is the decomposition of organic matter by the microbial flora. The saprophytic organisms are the most active in this biochemical process; they have optimum temperatures that are near the ambient temperature of many streams during the summer months. In a stream polluted with sewage, the pathogenic and indicator organisms are also present and perform a minor role in the self-purification process. The temperature of the stream water even during the summer is below the optimum for pollution associated bacteria. Increasing the water temperature increases the bacterial multiplication rate when the environment is favorable and the food supply is abundant. Increasing the water temperature within the growth range of the bacteria causes a more rapid die-off when the food supply is limited. The decrease of bacterial numbers is higher during the summer than during the winter (Figure 3).

Unpolluted streams contain dissolved oxygen near saturation levels. When organic wastes are discharged into the stream, the biochemical process is aerobic - reducing the dissolved oxygen by oxidation and dilution. When the reaeration rate of the stream is low, the oxygen may be depleted by the bacterial metabolism of the increasing population.

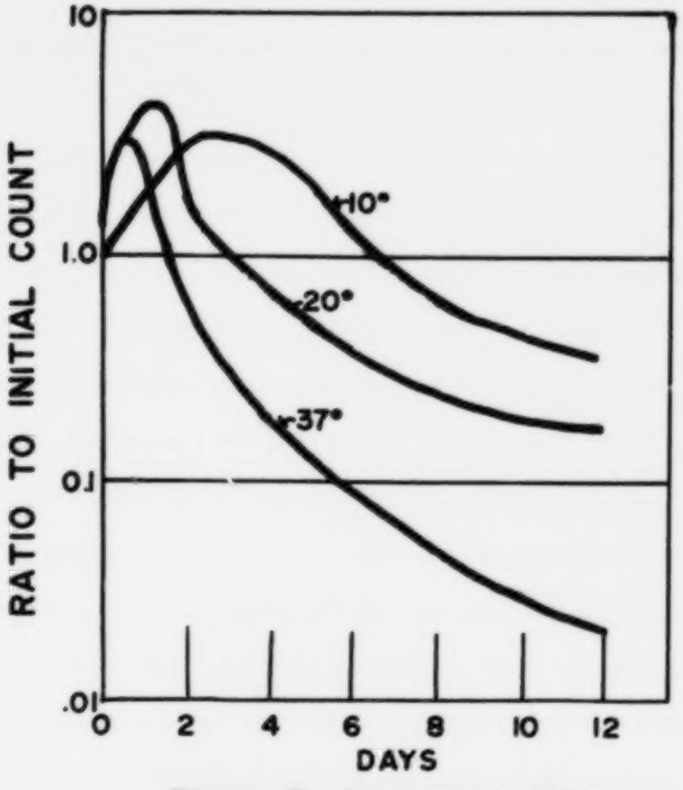

Figure 3. From Huekelekian, 1953, p. 27

As the available oxygen diminishes, the aerobic organisms die-off rapidly, sharply decreasing the natural purification process of assimilating the organic waste load. When this occurs there is a shift in the flora in the stream to the facultative anaerobic organisms. The ultimate result of anaerobic decomposition may be the same as that of the aerobic, but it is very slow and less desirable (Fair, Geyer, and Morris, 1958).

As the temperature increases, the dissolved oxygen solubility decreases. When a warm water discharge is near a sewage treatment plant outfall, self-purification can be very effective if the organic waste load is not excessive.

The impounding of water may improve the water quality by reducing sediments, color, bacteria and temperature. Ingols (1957) found also that the pattern of reservoir discharge permitted slime development downstream during low flow and scouring of the slime during high flows. "Out of phase" dilution of the receiving stream could promote or retard stream self-purification (Berger, 1961). Berger as well as Renn (1957) agree that the rate of stream reaeration increased at higher temperatures.

Growth and Survival

Chambers and Clarke (1966) state: "Many bacteria reproduce in water: among the genera that will grow in water of unquestioned potable quality are: (1) Pseudomonas, (2) Xanthomonas, (3) Achromobacter, (4) Escherichia, (5) Aerobacter, (6) Streptococcus, (7) Desulfovibrio, and (8) Crenothrix."

Renn (1957) points out that elevating the stream temperature can be favorable for those bacteria that can multiply in water by inducing the recurring cycles of life and death more rapidly. However, enteric pathogens have highly selective requirements. They cannot multiply or survive well in natural water, so they die-off more rapidly.

Because higher temperatures in a stream polluted with sewage generally result in increased bacterial numbers, low temperatures are not conducive to rapid growth. Stream temperatures of 1° to 8°C (33.8-46.4°F) may surpress growth and multiplication, and act as a preservative as in the storage of samples for bacterial analyses. Freezing of water can result in reduced microbial populations by killing off a majority of the microorganisms. Streams that have high organic waste loads and low temperatures tend to develop slime organisms, generally Sphaerotilus.

A study of the Columbia River in Oregon showed Sphaerotilus growths to be maximum at water temperatures of 10° to 15°C (50°-59°F). Growth ceased when temperatures dropped below 4°C (39.2°F) and resumed when temperatures increased above 4°C (39.2°F). Infestations of Sphaerotilus may occur at temperatures below 10°C (50°F) if the growing period is sufficiently long (Amberg and Cormack, 1960). Beds of Sphaerotilus slime may extend farther downstream from a waste outfall in the winter than in the summer when warmer temperatures seem to inhibit the efficiency of food conversion by the organism (Dondero, 1961).

Clark et al. (1964) assessed the value of bacterial indicators of pollutions as indicators of viral pollution by studying the relative survival of the organisms in water. They observed that the lower the temperature the longer the survival for both bacteria and viruses. The enteric bacteria had survival times in proportion to the degree of pollution, the greater the pollution the longer the survival time. The increased quantity of nutrients present in the more polluted water may account for the longer survival time of the bacteria. The viruses studied survived longer in the "clean" Little Miami River water and in the grossly polluted raw sewage than in the moderately polluted Ohio River water. They also point out the difficulty in generalizing on comparative survival times because the different genera of organisms may have different survival times in the different stream environments (Table 1).

Summary

The temperature of stream water, even during the summer, is below the optimum for pollution-associated bacteria. Increasing the water temperature increases the bacterial multiplication rate when the environment is favorable and the food supply is abundant. Increasing the water temperature within the growth range of the bacteria causes a more rapid die-off when the food supply is limited.

TABLE 1

AVERAGE TIME IN DAYS FOR 99.9 PERCENT REDUCTION IN ORIGINAL TITER OF INDICATED MICROORGANISMS AT THREE TEMPERATURES

(From Clarke, Berg, Kabler and Chang, p. 526, 1964)

Microorganisms	Little Miami River			Ohio River			Sewage		
	28°C	20°C	4°C	28°C	20°C	4°C	28°C	20°C	4°C
Poliovirus I	17	20	27	11	13	19	17	23	110
ECHO 7	12	16	26	5	7	15	28	41	130
ECHO 12	5	12	33	3	5	19	20	32	60
Coxsackie A9	< 8	< 8	10	5	8	20	6	No Data	12
A. aerogenes	6	8	15	15	18	44	10	21	56
E. coli	6	7	10	5	5	11	12	20	48
S. fecalis	6	8	17	9	18	57	14	26	48

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III. FRESHWATER FISHES

Introduction

Changes in fish populations can result from the many types of artificial cooling and heating of natural waters. These changes result from the discharge of condensed water from steam-electric generating plants, distillery effluents, and irrigation waters. Stream temperatures are raised also by the removal of stream bank trees and other vegetation. Water temperatures are often elevated in excess of the air temperature by absorption of heat by the stream bed. Yet another type of thermal pollution results from the discharge of cold-water from stratified impoundments; this water may provide an ideal habitat for trout and other cold-water fish when sufficient dissolved oxygen is present.

General Effects

The effects of temperature on fish are acute because fish do not possess an efficient method to compensate their internal temperature against a temperature change in the water in which they are immersed. If a more favorable temperature is available, fish do have the ability to seek it out.

Chemical reactions are accelerated within the body cells with elevated temperatures. Prosser (1955) discusses four possible death mechanisms, although he does not attach specific temperature values to various death processes. These are: an enzyme inactivity caused by the acceleration of the enzyme reaction to such a state that it is no longer effective; coagulation of cell proteins; melting of cell fats; reduction in the permeability of cell membranes. Cells may also be killed by toxic action of the products of metabolism and, incomplete metabolism accumulating in the cells (Ellis, 1947).

According to Brett (1960), temperature acts in a variety of different ways; it can be lethal, cause a reduction of activity, and limit reproduction. The slow rate of acclimation appears to result in greater mortalities from cold despite the ability of fish to withstand lower temperatures.

Sudden Temperature Changes

The effect of thermal shock on fish can be more harmful than continued exposure to a higher temperature (Cairns, 1956). In studies with rainbow trout, Threinen (1958) found that death would result from an instantaneous or rapid increase (shock) of 11.1°C (20°F) above an acclimation temperature of 12.2°C (54°F), however, a similar increase of 8.4°C (15°F) could be tolerated from a temperature of 10.6°C (51°F). A rise of the acclimation temperature from 12.2 to 18.4°C (54-65°F) during a 24-hour period permitted trout to withstand a temperature of 23.4°C (74°F) with only minor distress for short periods.

Fish having the ability to adapt to higher temperatures faster and over a larger gradient often are attracted to artificially heated water without a resultant mortality. However, mortality often results when these fish return to cold water. Agersborg (1930) found fish dying when they attempted to return from heated water (26.1°C - 79°F) to the colder stream (0°C - 32°F); death occurred even when fish moved into water that was 5.6°C (10°F) cooler. Falkner and Houston (1966) found that the mean erythrocytic (red blood cell) volume underwent a transient decrease while total blood iron (and presumably haemoglobin and mean erythrocytic iron content) fell slightly after goldfish which had been acclimated to 20°C (68°F) were subjected to an abrupt increase of 10°C (18°F). Heinicke and Houston (1965) concluded that while thermal shock induces initial deviations in iono- and osmoregulatory ability the goldfish can compensate for these changes during the acclimation period through respiratory activities, and restore its original ionic status.

A rise in temperature from 10°C to 20°C (50-68°F) reduced resistance to a decrease in oxygen in perch, roach, and mirrorcarp. In rainbow trout the resistance was lowered considerably between a rise in temperature from 10°C to 16°C (50-60.8°F) (Downing and Merkens, 1957).

Acclimation

The importance of acclimation temperatures has long been known to fish hatchery personnel and physiologists working on lethal temperatures. Much of the work on lethal temperatures is of little value because holding temperatures and durations are not given. Springtime mortalities often result from fish being subjected to warmer water temperature after acclimation to cold winter temperatures.

Doudoroff, in Brown (1957), discussing the work of Fry, et al., (1946) and Fry (1947) concludes that fish could stand brief exposures to considerably higher temperatures without showing distress when they had been acclimated to the maximum possible temperature. However, the fish suffered mortality when they had been acclimated to low temperatures. Similarly, Doudoroff in discussing the work of Hart (1952) noted considerable geographic, seasonal, and other variations of the resistance to heat of some species of fish acclimated to the same temperature.

Doudoroff in discussing the rate of acclimation summarized the work of many workers and concluded that the increased heat resistance (the ability to withstand increased water temperatures) is acquired usually at a very fast rate in the high temperature range from 26°C to 30°C (78.8-86.0°F) although there may be a latent period of one or longer days in which virtually no change takes place in the upper lethal temperatures. Most of the resulting increase was achieved in a period of one to three days. There was little or no loss of resistance in the first three days. Thus, if a fish has acquired a higher heat resistance it will not be lost rapidly on subsequent exposures to low temperatures.

Jones (1964) in discussing the work of Sumner and Wells noted that the tolerance to high temperatures once acquired may persist for considerable periods after return of the fish to the acclimation temperature. The time of acclimation need not be continuous. An intermittent exposure to a different temperature for sufficient hours per day can produce the same acclimation temperature as a continuous exposure.

The acclimation of fish is important in determining the maximum environmental temperature in which fish can survive. Jones (1964) discusses how the resistance time shortens with a progressive rise in temperature until the fish succumbs to an ultimate lethal temperature. As the acclimation temperature rises the thermal death point rises, but it rises at a slower rate. Accordingly, experiments on roach show that for every 3-degrees rise in acclimation temperature the thermal death point rises only 1-degree C (1.8°F).

Maximum Temperatures

Maximum temperatures have been determined for numerous species of fish (Table 2). Tnese temperatures are important in determining the absolute temperature at which a fish can survive, but they are often higher than the maximum temperature at which a population can survive.

Alabaster (1962) found that heated effluents, by virtue of their high temperatures only, may be lethal to caged trout and coarse fish acclimated to normal river temperatures during the summer and may also occasionally kill free-living fish which are near effluent outfalls when temperatures increase rapidly. Small free-living fish are principally affected, large fish apparently are able to swim away to safety. He concludes further that where the water temperature of the whole river is above normal because of mixing with continuous discharge of heated effluent,

TABLE 2

TOLERANCE LIMITS FOR CERTAIN FISHES

Values are LD50 temperature tolerance limits, i.e., water temperatures survived by 50 percent of the test animals. Counts were made by observing or estimating the number killed during exposure, or within a reasonable time thereafter in which it could be safely assumed that all deaths were attributable to the temperature effects.

(This Table Taken in Part From Anon., 1962)

Fish	Acclimated to		Lower Limit			Upper limit		
	°C	(°F)	°C	(°F)	Hr	°C	(°F)	Hr
Bass, largemouth (*Micropterus salmoides floridanus*)	20.0°C	(68.0°F)	5.0°C	(41.0°F)	24	32.0°C	(89.6°F)	72
	30.0°C	(86.0°F)	11.0°C	(51.8°F)	24	24.0°C	(93.2°F)	72
Bluegill (*Lepomis macrochirus macrochirus*)	10.0°C	(50.0°F)				29.0°C	(82.4°F)	24
	30.0°C	(86.0°F)				36.0°C	(96.9°F)	24
Bluegill (L. *macrochirus purpurescens*)	15.0°C	(59.0°F)	3.0°C	(37.4°F)	24	31.0°C	(87.8°F)	60
	30.0°C	(86.0°F)	11.0°C	(51.8°F)	24	34.0°C	(93.2°F)	60
Bullhead (*Ameiurus n. nebulosus*, A. n. *narmoratus*)	20.0°C	(68.0°F)	1.0°C	(33.8°F)	24	32.0°C	(89.6°F)	96
	30.0°C	(86.0°F)	7.0°C	(44.6°F)	24	35.0°C	(95.0°F)	96
Catfish, channel (*Ictalurus lacustris lacustris*, I.l *punctatus*)	15.0°C	(59.0°F)	0.0°C	(32.0°F)	24	30.0°C	(86.0°F)	24
	25.0°C	(77.0°F)	6.0°C	(42.8°F)	24	34.0°C	(93.2°F)	24
Chub, creek (*Semotilus* a. *atromaculatus*)	5.0°C	(41.0°F)				25.0°C	(77.0°F)	96
	25.0°C	(77.0°F)				32.0°C	(89.6°F)	96
Dace, blacknose (*Rhinichthys* a. *atratulus*, R.a. *meleagris*)	5.0°C	(41.0°F)				30.0°C	(80.6°F)	340
	25.0°C	(77.0°F)	5.0°C	(41.0°F)	24	29.0°C	(84.2°F)	340
Goldfish (*Carassius auratus*)	2.0°C	(35.6°F)				28.0°C	(82.4°F)	14
	17.0°C	(62.6°F)	0.0°C	(32.0°F)	14	34.0°C	(93.2°F)	14
Greenfish (*Girella nigricans*)	24.0°C	(75.2°F)	5.0°C	(41.0°F)	14	36.0°C	(96.8°F)	14
	37.0°C	(98.6°F)	15.0°C	(59.0°F)	14	42.0°C	(107.6°F)	14
	12.0°C	(53.6°F)	5.0°C	(41.0°F)	120	30.0°C	(86.0°F)	120
	18.0°C	(64.4°F)	13.0°C	(55.4°F)	72	31.0°C	(87.8°F)	120
Killifish (*Fundulus heteroclitus*)	14.0°C	(57.2°F)	1.0°C	(33.8°F)	48	32.0°C	(89.6°F)	
	20.0°C	(68.0°F)	2.0°C	(35.6°F)	48	34.0°C	(93.2°F)	
Minnow, fathead (*Pimephales promelas*)	20.0°C	(68.0°F)	2.0°C	(35.6°F)	24	32.0°C	(89.6°F)	133
	30.0°C	(96.0°F)	11.0°C	(51.8°F)	24	33.0°C	(91.4°F)	133
Minnow, blunt-nose (*Hyborhynchus notatus*)	15.0°C	(59.0°F)	1.0°C	(33.8°F)	24	31.0°C	(87.8°F)	133
	25.0°C	(77.0°F)	8.0°C	(46.4°F)	24	33.0°C	(91.4°F)	133

TABLE 2, Continued

Fish	Acclimated to °C	(°F)	Lower Limit °C	(°F)	Hr	Upper Limit °C	(°F)	Hr
Mosquito fish	15.0°C	(59.0°F)	2.0°C	(35.6°F)	24	35.0°C	(95.0°F)	66
(*Grambusia affinis*	35.0°C	(95.0°F)	15.0°C	(59.0°F)	24	37.0°C	(98.6°F)	66
affinis, G.a. *holbroki*)								
Perch (*Perca flavescens*)	5.0°C	(41.0°F)				21.0°C	(69.8°F)	96
Winter	25.0°C	(77.0°F)	4.0°C	(39.2°F)	24	30.0°C	(86.0°F)	96
Summer	25.0°C	(77.0°F)	9.0°C	(48.2°F)	24	32.0°C	(89.6°F)	96
Shad, gizzard	25.0°C	(77.0°F)	11.0°C	(51.8°F)	24	34.0°C	(93.2°F)	48
(*Dorosoma cepedianum*)	35.0°C	(95.0°F)	20.0°C	(68.0°F)	24	37.0°C	(98.6°F)	48
Shiner, common	5.0°C	(41.0°F)				27.0°C	(80.6°F)	133
(*Notropis cornutus*	25.0°C	(77.0°F)	4.0°C	(39.2°F)	24	31.0°C	(87.8°F)	133
frontalis)	30.0°C	(86.0°F)	8.0°C	(46.4°F)	24	31.0°C	(87.8°F)	133
Shiner, common	25.0°C	(77.0°F)				32.0°C	(89.6°F)	133
(*Notropic cornutus*	30.0°C	(86.0°F)				34.0°C	(93.2°F)	133
chrysocephalus)								
Shiner, lake	5.0°C	(41.0°F)				23.0°C	(73.4°F)	133
(N. *atherinoides*)	15.0°C	(59.0°F)	2.0°C	(35.6°F)	24	29.0°C	(84.2°F)	133
	25.0°C	(77.0°F)	8.0°C	(46.4°F)	24	31.0°C	(87.8°F)	133
Shiner, golden	20.0°C	(68.0°F)	8.0°C	(46.4°F)	24	32.0°C	(89.6°F)	66
(*Notemigonus* c.	30.0°C	(86.0°F)	11.0°C	(51.8°F)	24	35.0°C	(95.0°F)	66
crysoleucas, N.c. *auratus*)								
Sucker, common	15.0°C	(59.0°F)						
(*Catostomus commersoni*)	25.0°C	(77.0°F)	5.0°C	(41.0°F)	24	29.0°C	(84.2°F)	133
Sunfish	10.0°C	(50.0°F)				28.0°C	(82.4°F)	24
(*Lepomis gibbosus*)	30.0°C	(86.0°F)				24.0°C	(75.2°F)	24
Trout, brook	3.0°C	(37.4°F)				23.0°C	(73.4°F)	133
(*Salvelinus fontinalis*)	20.0°C	(68.0°F)				25.0°C	(77.0°F)	133
	25.0°C	(77.0°F)				25.0°C	(77.0°F)	133

coarse fish populations may be reduced locally when the mean daily temperature reaches 30°C (86°F) and increased when the water is not warmed to more than 26°C (78.8°F).

Wells (1914) concluded that the resistance of fish to temperature varies with species and size of fish. There is no definite maximum temperature for a given species of fish; it varies with the fish's rate of heating, size, and physiological condition.

A temperature need not kill the fish directly for it to be lethal. Brook trout were found to be comparatively slow in catching minnows at 17.2°C (63°F) and virtually incapable of catching minnows at 21°C (70°F). This resulted in the trout virtually starving to death (Anon., 1962).

As a maximum temperature for cold water fishes the Pennsylvania Department of Health recommends*: that no wastes or waters shall be added from any source having temperatures in excess of that of the receiving waters except that during the period October through May, when stream temperatures are below 14.5°C (58°F) the temperature of wastes discharged to the streams shall not exceed 14.5°C (58°F). To allow for the normal production of aquatic life in warm water lakes and streams it is recommended that water temperatures resulting from thermal discharge shall not exceed

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* Anon., 1962. Heated discharges . . . their effect on streams. Rep. by the Advisory Committee for the control of stream temperatures to the Pa. Sanitary Water Board. Pa. Dept. Health, Harrisburg, Publ. No. 3, 108 pp.

30°C (93°F) exclusive of the required mixing zone and in no case shall this peak temperature prevail for more than eight hours in any 24-hour period.

Preferred Temperature

It is generally acknowledged that fish can live for short periods of time in higher than normal temperatures, but at these temperatures fish cannot perpetuate their populations. Fish are extremely sensitive to temperature and seek out the temperature that is best for their survival. The temperature that fish seek out is termed "preferred temperature;" these are listed for several species of fish in Tables 3 and 4 and Figures 4 and 5.

Windermere char eggs hatched in 45 days at 10°C (50°F), and in 95 days at 4°C (39.2°F) (Swift, 1965). Mortality to some extent occurred at 8°C (46.4°F), with total mortality occurring at 12°C (53.6°F).

Ferguson (1958) concluded that the level of thermal acclimation influences the range of temperature preferred. In general, the preferred temperature is considerably higher than the acclimation temperature at lower thermal acclimations, but this difference decreases up to the final preferred temperature where both coincide. A final preferred temperature and the relation between acclimation and preferred temperature is characteristic for the species.

Tarzwell (1957) concluded that while temperatures higher than the optimum, and high temperatures of short duration, 23.9 to 27.8°C (75 to 82°F),

TABLE 3

THE FINAL TEMPERATURE PREFERENDA FOR VARIOUS SPECIES OF FISH AS DETERMINED BY LABORATORY EXPERIMENTS

Young of the Year or Yearling Fish Were Used, Except as Noted.
(This Table Taken in Part From Ferguson, 1958)

Species	Final Preferendum	Authority
Bluegill (*Lepomis macrochirus*)	32.3°C (90.1°F)	Fry and Pearson (MS, 1952)
Bass, Largemouth (*Micropterus salmoides*)	30.0-32.0°C (86-89.6°F)	Fry (MS, 1950)
Carp (*Cyprinus carpio*)	32.0°C (89.6°F)	Pitt, Garside and Hepburn (1956)
Pumpkinseed (*Lepomis gibbosus*)	31.5°C (88.7°F)	Anderson (MS, 1951)
Goldfish (*Carassius auratus*)	28.1°C (78.8°F)	Fry 1947
Bass, Smallmouth (*Micropterus dolomieu*)	28.0°C (82.4°F)	Fry (MS, 1950)
Grass Pickeral (*Esox vermiculatus*)	26.6°C (78.8°F)	Berst and Lapworth (MS, 1950)
Yellow Perch (*Perca flavescens*)	24.2°C (75.6°F)	Ferguson (1958)
Muskellange (*Esox masquinongy*)	24.0°C (75.2°F)	Jackson and Price (MS, 1949)
Burbot (*Lota lota lacustris*)	21.2°C (70.2°F)	Crossman, Ireyawa and Pecicock (MS, 1953)
Yellow Perch (*Perca flavescens*)	21.0°C (69.8°F)	McCracken and Starkma (MS, 1948)
Brown Trout (*Salmo trutta*)	12.4-17.6°C (54.3-63.7°F)	Tait (MS, 1958)
Brook Trout (*Salvelinus fontinalis*)	14.0-16.0°C (57.2-60.8°F)	Graham (1948)
Rainbow Trout (*Salmo gairdnerii*)	13.6°C (56.5°F)	Garside and Tait (MS, 1958)
Lake Whitefish (*Coregonus clupeaformis*)	12.7°C (54.9°F)	Tompkins and Fraser (MS, 1950)
Lake Trout (*Salvelinus namaycuch*)	12.0°C (53.6°F)	McCauley and Tait (MS, 1956)

TABLE 4

FIELD OBSERVATIONS ON VARIOUS SPECIES OF FISH AND ASSOCIATED TEMPERATURES

Some temperatures are estimates derived from Ferguson's tabled or figured data. August distributions and temperatures were used wherever possible. These figures represent the temperature of the water strata in which the fish seemed to concentrate. It is judged these represent preferred natural temperature.

(This Table Taken in Part from Ferguson, 1958)

Species	Temperature	Water	Location	Author
Bass, Largemouth (*Micropterus salmoides*)	26.6-27.7°C (80.0-81.9°F)	Norris Reservoir	Tennessee	Dendy 1948
Bass, Spotted (*Micropterus punctulatus*)	23.5-24.4°C (74.1-75.9°F)	Norris Reservoir	Tennessee	Dendy
Walleye (*Stizostedion* v. *vitreum*)	20.6°C (69.1°F)	Trout Lake	Wisconsin	Hile and Juday, 1941
Walleye (*Stizostedion* v. *vitreum*)	22.7-23.2°C (72.9-73.8°F)	Norris Reservoir	Tennessee	Dendy 1948
Gizzard Shad (*Dorosoma cepedianum*)	22.5-23.0°C (72.5-73.4°F)	Norris Reservoir	Tennessee	Dendy
Freshwater Drum (*Aplodinotus grunniens*)	21.6-22.2°C (70.9-72.0°F)	Norris Reservoir	Tennessee	Dendy
Rock Bass (*Ambloplites rupestris*)	14.7-21.3°C (58.5-70.3°F)	Lakes	Wisconsin	Hile and Juday, 1941
Rock Bass (*Ambloplites rupestris*)	20.7°C (69.3°F)	Streams	S. Ontario	Hallam 1958
Yellow Perch (*Perca flavescens*)	21.2°C (70.2°F)	Lake Opeongo	Ontario	Present Work
Yellow Perch (*Perca flavescens*)	21.0°C (69.8°F)	Costello Lake	Ontario	Present Work
Yellow Perch (*Perca flavescens*, small)	12.2°C (54.0°F)	Muskellunge Lake	Wisconsin	Hile and Juday, 1941
Yellow Perch (*Perca flavescens*, larger)	20.2°C (68.4°F)	Muskellunge Lake	Wisconsin	Hile and Juday, 1941

TABLE 4, continued

Species	Temperature	Water	Location	Author
Yellow Perch (*Perca flavescens*, larger)	20.2°C (68.4°F)	Silver Lake	Wisconsin	Hile and Juday, 1941
" "	21.0°C (69.8°F)	Nebish Lake	Wisconsin	Hile and Juday, 1941
" "	20.8°C (69.5°F)	Trout Lake	Wisconsin	Hile and Juday, 1941
" "	19.7°C (67.5°F)	Lake Nipissing	Ontario	Present Work
Bass, Smallmouth (*Micropterus dolomieui*)	20.3-21.3°C (68.5-70.3°F)	Nebish Lake	Wisconsin	Hile and Juday, 1941
" "	21.4°C (70.5°F)	Streams	S. Ontario	Hallam 1958
Sauger (*Stizostedion canadense*)	18.6-19.2°C (65.1-66.6°F)	Norris Reservoir	Tennessee	Dendy 1948
Brook Trout (*Salvelinus fontinalis*)	14.2-20.3°C (57.6-68.5°F)	Moosehead Lake	Maine	Cooper and Fuller
" "	15.7°C (60.3°F)	Streams	S. Ontario	Hallam 1958
" "	12.0-20.0°C (53.6-68.0°F)	Redrock Lake	Ontario	Baldwin 1948
Mottled Sculpin (*Cottus bairdii*)	16.5°C (61.7°F)	Streams	S. Ontario	Hallam 1958
Brook Trout x Lake Trout (*Salvelinus* hybrid)	13.1°C (55.6°F)	Jack L. Sproule Lake	Ontario	Martin and Baldwin, 1958
White Sucker (*Catostomus commersonnii*)	11.8-20.6°C (53.3-69.1°F)	Musk, Trout Silver	Wisconsin	Hile and Juday, 1941
White Sucker (*Catostomus* c. *commersonnii*)	14.1-18.3°C (57.4-64.9°F)	Moosehead Lake	Maine	Cooper and Fuller, 1945
Round Whitefish (*Prosopium cylindraceum*)	13.9-17.5°C (57.0-63.5°F)	Moosehead Lake	Maine	Cooper and Fuller, 1945
Alewife (*Pomolobus pseudoharengus*)	4.4- 8.8°C (39.9-47.8°F)	Cayuga Lake	New York	Galligan 1951

TABLE 4 , continued

Species	Temperature	Water	Location	Author
Lake Trout (*Salvelinus namaycush*)	10.0-15.5°C (50.0-59.0°F)	Cayuga Lake	New York	Galligan 1951
" "	14.0°C (57.2°F)	White Lake	Ontario	Kennedy 1941
" "	11.0-11.5°C (51.8-52.7°F)	Moosehead Lake	Maine	Cooper and Fuller, 1945
" "	8.0-10.0°C (46.4-50.0°F)	Louisa Redrock	Ontario	Martin 1952
American Smelt (*Osmerus mordax*)	12.8°C (55.0°F)	Lake Champlain	New York	Greene 1930
" "	6.6- 8.3°C (43.9-47.9°F)	Cayuga Lake	New York	Galligan 1951
Lake Whitefish (*Coregonus clupeaformis*)	11.4-11.9°C (52.5-53.5°F)	Moosehead Lake	Maine	Cooper and Fuller, 1945
Longnose Sucker (*Catostomus catostomus*)	11.0-11.6°C (51.8-53.0°F)	Moosehead Lake	Maine	Cooper and Fuller, 1945
Burbot (*Lota lota maculosa*)	10.8-11.4°C (51.4-52.5°F)	Moosehead Lake	Maine	Cooper and Fuller, 1945
Coregonys (*Leucichthys artedi*)	8.0-10.0°C (46.4-50.0°F)	Lake Nipissing	Ontario	Fry 1937
" " (Cisco or Lake Herring)	5.5- 7.2°C (41.9-44.8°F)	Cayuga Lake	New York	Galligan 1951

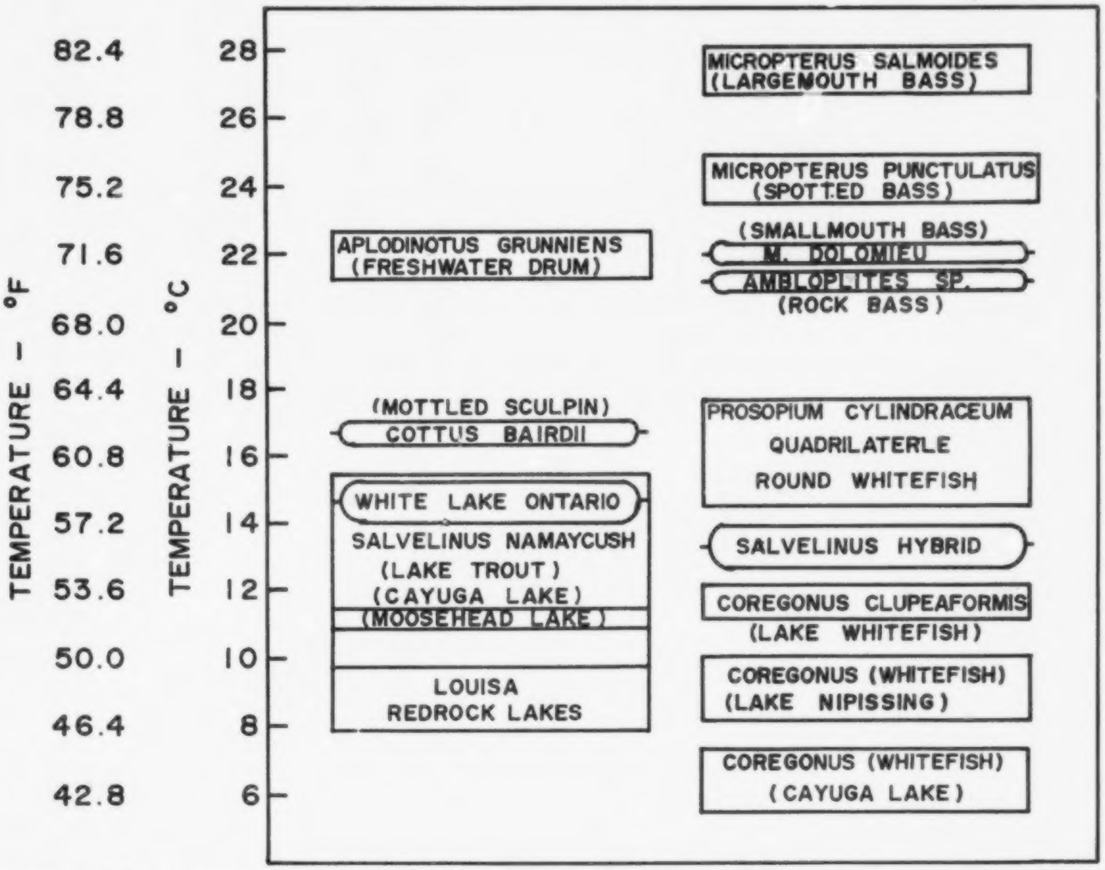

FIGURE 4 FIELD OBSERVATIONS OF FISH AND ASSOCIATED TEMPERATURES DURING MIDSUMMER (AUGUST MOSTLY). THE DEPTH OF EACH RECTANGLE CORRESPONDS TO THE TEMPERATURE RANGE. POINTERS ON LATERALLY ROUNDED FIGURES REPRESENT A DERIVED AVERAGE. VERTICAL RELATIONS ONLY ARE IMPORTANT (FERGUSON, 1958),

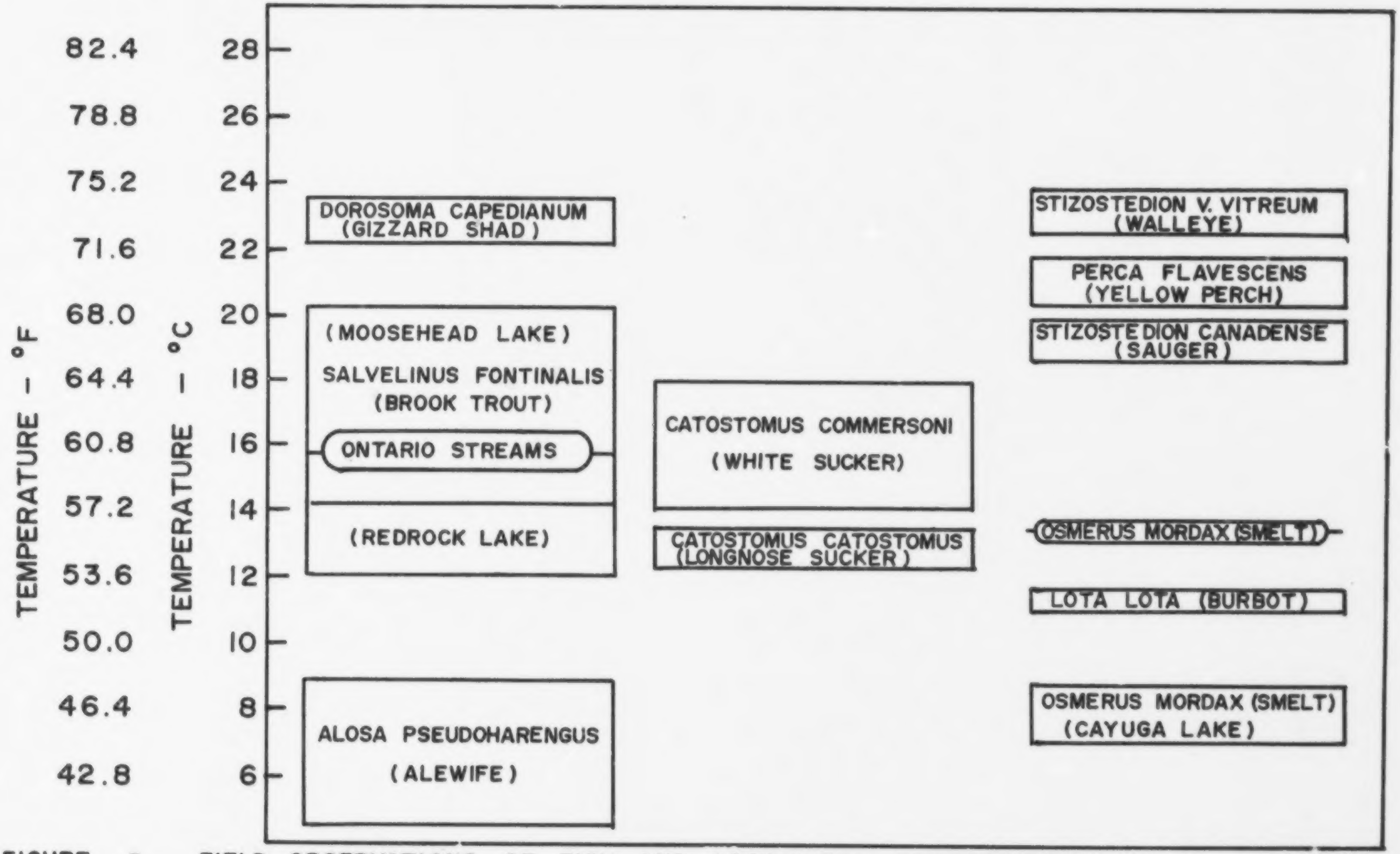

FIGURE 5. FIELD OBSERVATIONS OF FISH AND ASSOCIATED TEMPERATURES DURING MIDSUMMER (AUGUST MOSTLY). THE DEPTH OF EACH RECTANGLE CORRESPONDS TO THE TEMPERATURE RANGE. POINTERS ON LATERALLY ROUNDED FIGURES REPRESENT A DERIVED AVERAGE. VERTICAL RELATIONS ONLY ARE IMPORTANT (FERGUSON, 1958).

may not kill trout they produce environmental conditions favorable for the production of coarse fish.

One unusual set of data collected on preferred temperatures of rainbow trout by Garside and Tait (1958) showed that the preferred temperatures were inversely related to the acclimation temperature. They state, "Fish cannot lose heat because they must pass considerable quantities of water through their respiratory system in order to compensate for the low quantities of dissolved oxygen contained in waters possessing a higher temperature. With the animal passing higher quantities of heated water across their gills the body temperature of the animal must rise."

Effect of Temperature on Toxicity

Effects of artificially induced temperature changes can result in fish mortalities; as temperature increases the toxicity of certain materials increases.

The Prevention Subcommittee of the Central Water Committee, Ministry of Health, England, (Anon., 1949) states, "...increase in temperature also increases the lethal effect of toxic substances to fish." For example a rise in temperature from 8°C (46°F) to 18°C (64°F) approximately doubled the toxicity of a low concentration of potassium cyanide.

The toxicity of chloride concentrations has been shown to be dependent on temperature. The temperature has a significant effect on the time of both initial and final mortalities, the rate of mortality, and the duration of the mortality for rainbow trout. It has been postulated that the metabolic rate of the fish, which affects the rate to which fluoride is toxic to rainbow trout, is affected by the increased temperature of the fish, Angelovic (1961).

Benefits

Trembley (1960) concluded that most fish species are attracted to and invade heated water areas from late September until early June. Attraction to heated water has been observed in England, and has been reported frequently in America. This adds to the recreational value of localized areas, because angling can be continued throughout the winter when there may be little or no fishing in other areas. Trembley found that one of the disadvantages to providing winter fishing is that fish leave the heated-water zone in the hot summer months.

Another benefit of artificially induced temperature changes is the production of trout and other cold water fish in the reach downstream from reservoirs. Low level penstock discharges from stratified reservoirs often lowers the temperature in the receiving stream to 12.8°C (55°F) and it may not exceed 20°C (68°F) even in summer (Mackenthun et al., 1964).

Summary

1. Warm water fish can survive temporarily in waters heated artificially to 33.9°C (93°F); even at 30°C (86°F) coarse fish populations, such as roach, perch, gudgeon, tench and carp, are reduced. In cold weather, stream temperature should be substantially below 33.9°C (93°F) to prevent mortalities when fish move through excessive stream gradients.
2. Streams supporting cold water non-anadromous fish populations should not receive heated effluents that will raise receiving stream temperatures above 14.5°C (58°F). In cold weather, stream temperature should be below 14.5°C (58°F) to prevent mortalities.
3. Sudden changes in temperature can be more harmful to some species of fish than continued exposure to a higher temperature.
4. Fish can adapt to higher temperatures faster than to lower temperatures.
5. The maximum temperature for a given species of fish varies with the fish's rate of heating, size, and physiological condition.
6. Fish may starve at elevated temperatures because of their inability to capture food.
7. Fish seek out a preferred temperature at which they can best survive which is several degrees below their lethal temperature.
8. The toxic effects to fish of certain materials increase with temperature.
9. Certain benefits, including open water winter fishing in otherwise ice covered areas and a cold water fisheries downstream from reservoirs, can be derived from artificially induced temperature changes. The

benefits of fish being attracted to heated water in the winter months may be negligible compared to fish mortalities that may result when the fish return to the cooler water; lethal temperatures may result from heated discharges in the summer months.

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IV. MARINE, ESTUARINE AND ANADROMOUS FISHES

Introduction

Because a growing demand for electricity supplied by steam or nuclear generators has increased the need for ample water, both for cooling and thermal waste assimilation, larger areas of fresh and marine waters will receive significant temperature elevations (Mihursky and Kennedy, 1967). Future emphasis will be away from the use of inland waters, toward the utilization of estuarine and marine resources (Naylor, 1965). The protection of fishes in the estuarine and marine areas, as well as anadromous fishes that must move through areas of heated water is becoming an increasing problem.

General Temperature Effects

Researchers, studying the effects of fluctuating temperatures on fishes, have taken two approaches: one method of study is to observe the reactions of fishes in their natural habitat; the other method is to remove representative samples of fish from the natural habitat to the laboratory and observe them under selected test conditions. Both methods of study have been used equally well.

Physiology

The physiology of fishes is directly affected by temperature. Fishes are classed as poikilothermus or animals whose body temperature follows changes in environmental temperatures rapidly and precisely. In such animals the factors favoring heat loss tend to equal the factors producing body heat and the body temperature approaches environmental temperature (Prosser, et al., 1950; Kinne, 1963). In a majority of fishes the body temperature differs from that of the surrounding water by only 0.5-1.0°C (0.9-1.8°F) (Nikolsky, 1963). Therefore, one of the fundamental requirements of fishes is that the external temperature must be best suited to internal tissues (Brett, 1956). Cells exposed to heat undergo an increase in the viscosity of protoplasm. This increase is reversible to a point beyond which heat death occurs (Gunter, 1957). Various functions of an organism, such as reproduction, locomotion and growth may have different temperature ranges and these ranges should be known in order to evaluate the effects of temperature on that organism (Kinne, 1963). For example, according to Kinne (1963) and Naylor (1965), marine and brackish water organisms may increase or decrease osmotic regulation as a function of temperature.

Temperature fluctuations act on an organism in a variety of ways: a) metabolic rates are changed, b) reproduction is affected, c) distribution may be increased or decreased and d) tolerance limits are widened or narrowed.

Metabolism

Rates of metabolism and activity increase with increasing temperatures over most of the tolerated temperature range and then often cease suddenly near the upper lethal temperature. Such rates vary with different species, processes and levels or ranges of temperature and may be modified by salinity and oxygen factors (Kinne, 1963). Changes in metabolic rates, because of temperature fluctuations, may be signaling factors for spawning or migration (Nikolsky, 1963).

Reproduction

The effects of temperature on reproduction in many animals are confined to narrower ranges than the majority of functions (Kinne, 1963 and Gunter, 1957). Most marine animals have restricted temperatures for breeding. Rising temperatures in the spring induce development of the gonads and actual spawning takes place when a certain temperature level is reached, which varies for different species. Some fish spawn on a drop in temperature while others respond to a rise in temperature (Gunter, 1957). Because of narrow breeding requirements the survival of a species in heated waters does not preclude the possibility that the species may be prevented from breeding and may exist in an area by continued recruitment from outside (Naylor, 1965).

Development

Temperature changes affect fish development in several ways. Meristic characters and shape may be changed as well as embryonic development. Low temperatures slow down development and in some cases many marine and brackish water animals attain a larger final size because of their slow, long continued growth rather than rapid growth (Kinne, 1963).

Distribution and Ecology

Since temperature is the most important single factor governing the occurrence and behavior of life, it not only affects the distribution of a single species, it may also modify the species composition of a community or an ecosystem (Gunter, 1957 and Kinne, 1963). Tropical and subtropical fishes are more stenothermal (tolerate a narrow range of temperatures) than those of boreal and higher latitudes and marine forms are more stenothermal than fresh water ones (Nikolsky, 1963). In his publication on temperature effects on marine organisms Naylor (1965) noted that estuarine forms were more tolerant of heated effluents than marine forms and littoral species, and concluded that some coldwater stenothermal forms may be eliminated by heated discharges and some eurythermal (tolerate a wide range of temperatures) species may be increased. He also noted that temperature effects seem to be more pronounced in enclosed areas of estuaries and bays, while heat effects in open estuaries are least striking. In tropical areas, species live close to their thermal limits and effects of heated effluents are more pronounced, while in northern (Arctic) areas species may be 13 to 16°C (23.4 to 28.8°F) below their death temperatures and may not be as severely affected.

By testing species in the laboratory Brett (1956) noted that a slow rate of decrease in environmental temperature is of greater importance for maintaining life than a slow rate of increase. Lethal cold can be more important than lethal heat as a factor limiting the distribution of marine fish and as a hazard to some in their native habitats (Doudoroff, 1957).

Acclimation

The capacity to acclimate depends on the genetic background, environmental history and present physiological condition and age of the organism involved (Kinne, 1963). For example, the resistance of animals to cold is much more variable than resistance to heat and resistance to cold varies with size, smaller fish resisting best (Gunter, 1957).

Acclimation to different temperatures may involve changes in orientation, migration, and other behavioral aspects such as territorialism as well as biological rhythms (Kinne, 1963). In his experiments with marine fishes, Doudoroff (1957) noted that acclimatization to heat may be acquired very rapidly, the speed varying with heat. Also, brief or intermittent exposure to high temperatures can result in markedly increased resistance to heat which is not readily lost on subsequent exposure to low temperatures. However, it is the rapidity of the onset of low temperatures that probably causes death, outstripping the ability of fish to acclimate and resulting in greater mortalities that are due to cold in nature (Brett, 1960). Deaths resulting from the inability of fish to rapidly acclimate to lowering temperatures have been reported by Gunter and Hildebrand (1951) and Galloway (1951).

According to Kinne (1963) acclimation to low temperature usually tends to shift the lower thermal limits downward and acclimation to high temperatures tends to shift the upper limits upward. As a result the ability to acclimate affects the temperature ranges that a fish can tolerate.

Tolerance

The temperature tolerance of fish varies with their development, area of distribution and physiology. As noted earlier, estuarine forms are more tolerant of heated effluents than marine forms and littoral species (Naylor, 1965). However, Kinne (1963) reports that in general, the total range of temperature tolerated in the state of active life is smallest in marine forms and largest in brackish and fresh-water forms. Gradual changes are tolerated much better than sharp changes. Some species can stand a gradual change up to 30 or 35°C (86 or 95°F), but at the upper extreme, many organisms are killed by temperatures not far above those to which they are accustomed.

MARINE FISHES*

Marine fishes that inhabit the shore line areas, estuaries or bays are most often affected by temperature changes. The problem of thermal shock to pelagic (living or occurring in the open ocean) life histories is extremely critical in marine environments (Mihursky and Kennedy, 1967).

Eggs

The effects of salinity and temperature on the eggs of Pacific Cod (*Gadus macrocephalus*) were studied by Forrester (1964) and, Forrester and

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* In this report the term marine includes estuarine species.

Alderdice (1966). In the study by Forrester, eggs were held to completion of hatching in various combinations of salinity and temperature. Maximum hatching success was in the vicinity of 19 parts per thousand (ppt) salinity and 5°C (41.0°F). Forrester and Alderdice observed that the relationship between rate of development of cod eggs and water temperature was linear at temperatures of 5-11°C (41-51.8°F). Time to 50 percent hatching ranged from 8.5 days at 11°C (51.8°F) to 17 days at 5°C (41°F). Most successful hatching occurred at the lower temperature. One of the most noted variables in the study on eggs of the American smelt (*Osmerus mordax*) in Maine was the large increases in mortality during extreme fluctuations in daily water temperature of as much as 7°C (12.6°F) as observed by Rothschild (1961). Striped bass eggs (*Roccus saxatilis*) were found to survive in constant fluctuations of water temperatures ranging from 12.8-23.9°C (55-75°F) Albrecht (1964). The tolerance of eggs of four marine fishes was studied by Hubbs (1965). California killifish (*Fundulus parvipinnis*), topsmelt (*Atherinops affinis*), California grunion (*Leuresthes tenuis*) and mussel blenny (*Hypsoblennius sp.*) were incubated at a variety of temperatures. Larvae successfully hatched at temperatures between 16.6°C and 28.5°C (61.9-83.1°F), 12.8 (-)°C and 26.8°C (55-80.1°F), 14.8° C and 26.8°C (58.6-80.1°F) and 12.0 (-) and 26.8 (+)°C (53.6(-)-80.1(+)°F) respectively (Table 5).

Young

Larvae of some marine fish are pelagic in the early part of their life history, and temperature of the surrounding water determines the rate of

Table 5 - Temperature ranges reported for the hatching of eggs from various species of marine and anadromous fish.

Species	Lower Temp. (C)	Upper Temp. (C)	Remarks	Source
Roccus saxatilis	12.8	23.9	Survived Constant Fluctuations	Albrecht, 1964
Fundulus parvipinnis	16.6	28.5	Successful Hatching	Hubbs, 1965
Atherinops affinis	12.8	26.8	" "	" "
Leuresthes tenuis	14.8	26.8	" "	" "
Hypsoblennius sp.	12.0(-)	26.8(+)	" "	" "
Petromyzon marinus	15.0	25.0	Survival Range	McCauley, 1963
"	15.6	21.1	" "	Piavis, 1961
Oncorhynchus nerka	4.4-5.8	12.8-14.2	Threshold Temp.	Combs, 1965
O. tshawytscha	5.8	14.2	" "	Combs & Burrows, 1957
" "	9.4	14.4	" "	Seymour, 1956
" "	5.6	14.4	" "	Leitritz, 1962
All Salmon	5.8	12.8	" "	Anon., 1966

development from a pelagic form to an actively swimming form. The rate of development of the lemon sole (Parophrys vetulus) determines the number of young that reach the nursery grounds in Hecate Strait, British Columbia (Ketchen, 1956). Small annual differences in the temperature of sea water produce marked differences in the duration of the pelagic stage. Below average temperatures result in the larvae being carried by the currents for a longer period of time and more larvae are deposited on the nursery ground. Thus, temperature may govern the strength of a year class. A temperature of 6.2°C (43.1°F) seems to produce the best deposition of larvae. Increases in temperature increase the rate and shorten the time of development of herring (Clupea pallasi). A temperature increase from 4.4-10.7°C (40-51.1°F) shortened development time from 40 to 11 days (Blaxter, 1963).

In the estuarine environment, fishes are more susceptible to heat changes. However, as noted in the general discussion, fish in estuarine waters seem to tolerate a wider range of temperatures. Striped bass fingerlings (Roccus saxatilis) were able to tolerate 35°C (95°F) in laboratory tests (Talbot, 1966). According to Talbot (1966), Merriman (1941) studied the striped bass of the Atlantic coast and found the maximum temperature in the New England area to be 25°C to 27°C (77.0 to 80.6°F) with fish kills occurring at these temperatures. Juvenile striped bass have survived transfer between salt and fresh-water at temperatures in the range of 12.8-21.1°C (55-70°F) but they are not tolerant to changes from fresh-water to saltwater at 7.2°C (45°F) (Tagatz, 1961). Striped bass acclimated at 4.4°C (40°F) and tested for eight hours with increases in temperature of 2.3°C (3.5°F) at one hour intervals, had a median lethal dose (LD_{50}) of 23.9°C (75°F), (Trembley, 1960).

The larvae of Atlantic Menhaden (Brevoortia tyrannus) were able to survive longer when acclimated at cooler temperatures, than when acclimated to warmer temperatures. Acclimation temperature was more important to larval survival at test temperatures below 5.0°C (41°F) than at 5.0°C (41°F) and above. Larvae acclimated at 7 and 10°C (44.6 and 50°F) survived over twice as long at 4.5°C (40.1°F) as those acclimated at 12.5 or 15°C (54.5 or 59°F), (Lewis, 1965). The effects of salinity on temperature tolerances were checked by Lewis (1966), who found a temperature of 6°C (42.8°F) and below with zero ppt salinity lowered larval survival time to only a few hours. At a salinity of 5-30 ppt and a temperature of 4°C (39.2°F) larval survival was good. Lower and upper limits of salinity tolerance were increased with increasing temperature.

The relation of menhaden (B. tyrannus) to estuaries was studied by Reintjes and Pacheco (1966). A water temperature of 3°C (37.4°F) may be critical to larval survival. Larval menhaden can suffer mass mortalities when water temperatures fall below 3°C (37.4°F) for several days or chill rapidly. The matter of chill seems to be very important to estuarine fishes.

Doudoroff (1942) studied the resistance and acclimation of marine fishes to temperature changes. Young greenfish (Girella nigricans) were used in his tests. Heat resistance was gained rapidly and lost slowly. Resistance to chilling was lost slowly on warming and acquired no more rapidly on cooling. The changes of resistance to heat and to cold were found to be more or less independent and distinct phenomena. Acclimation to cold is slow, to heat, fairly fast. For these reasons injury by chilling is no less important as a possible limiting factor in the distribution of marine fishes than heat injury.

More active fishes are able to avoid harmful temperatures and to exercise selection in experimental gradient (Doudoroff, 1938). In the case of pelagic marine larvae, circumstances may dictate their survival. A mortality of marine fish larvae was noted in an area off Georges Bank. Currents carried the larvae from cold 7.8°C (46°F) water into warm layers of 20°C (68°F) water and large mortalities resulted (Colton, 1959).

A study of the effect of extreme temperatures on herring larvae (C. harengus) revealed an upper lethal temperature 22.0 to 24.0°C (71.6-75.2°F) and a lower lethal temperature of -0.75 to -1.8°C (30.6-29.1°F). Larvae were 6-8 millimeters long and acclimated to temperatures between 7.5 and 15.5°C (58.2-72.9°F) (Blaxter, 1960). Young topsmelt (Atherinops affinis) acclimated to temperatures of 20°C (68°F) had an upper 48 hour median tolerance limit (TL_m) of 31.8°C (89.1°F) and a lower 48 hour TL_m of 10.1°C (50.1°F), (Doudoroff, 1945). Young greenfish (Girella nigricans) acclimated to temperatures of 12-28°C (53.6-82.4°F) exhibited a lower 48 hour TL_m of 4.1 to 13°C (39.4-55.4°F) and a upper TL_m of 28.7 to 31.5°C (81.9-88.8°F), (Doudoroff, 1942). Temperature ranges reported for young fish are listed in Table 6 .

Adults

Adult fish are usually able to select their preferred temperatures, unless they are trapped in shallow waters or forced to migrate through heated or chilled areas. Fish kills have been reported in areas of shallow water. Atlantic round herring (*Etrumeus sadina*) and chum mackerel (*Scomber colias*) were observed dead and dying after several days of cold weather had dropped water temperatures in Pamlico Sound, North Carolina, to 5.2°C (41.4°F), (Wells, Wells and Gray, 1961). The effects of winter water conditions were also observed by Schwartz (1964). He noted that most fish sank when killed by lowered temperatures and would probably not be observed. In the area of high temperatures, alewives (*Alosa pseudoharengus*) died of heat shock after being herded into water of 26.7 - 32.2°C (80-90°F). The same species showed no effects when they entered a lagoon with 22.8°C (73°F) water (Trembley, 1960). Herring, in nature, have been found in almost all temperature ranges permitted by their resistance to temperature extremes. Herring at the appropriate season have an upper lethal temperature of 19.5 to 21.2°C (67.1 to 70.1°F) depending upon size and can survive short exposure to temperatures below -1.0°C (30.2°F), (Brawn, 1960).

Table 6 - Temperature ranges reported for young marine and anadromous fish.

Species	Acclimation Temp.(C)	Lower Lethal Temp.(C)	Upper Lethal Temp.(C)	Remarks	Source
O. tshawytscha	23	7.4		Approx. 4 days	Brett, 1952
	20		25.1	Approx. 7 days	"
O. kisutch	23	6.4		Approx. 4 days	"
	20		25.0	" 7 "	"
O. nerka	23	6.7		Approx. 4 days	"
	20		24.4	" 7 days	"
O. gorbuscha			23.9	Approx. 7 days	
O. keta	23	7.3		Approx. 4 days	"
	20		23.8	Approx. 7 days	"
Clupea harengus	7.5-15.5	-0.75to-1.8	22.0-24.0		Blaxter, 1960
Atherinops affinis	20	10.1	31.8	48 hr TL_m	Doudoroff, 1942b
Girella nigricans	12-28	4.1-13	28.7-31.5	48 hr TL_m	Doudoroff, 1942a

Adult white perch (*Roccus americana*) acclimated to 4.4°C (40°F) and tested for 8 hours with increases of 2.0°C (3.5°F) every hour exhibited a median lethal dose (LD_{50}) of 27.8°C (82.0°F), (Trembley, 1960). In a flowing water test with heat increases of 1.1°C (2°F) per hour saltwater killifish (*Fundulus heteroclitus*) acclimated at 7.2°C (45°F) had a LD_{50} of 37°C (99°F) (Trembley, 1961). Adult California killifish (*F. parvipinnis*) were tested by Doudoroff (1945). At acclimation temperatures of 14-28°C (57.2-82.4°F) the upper TL_m's, for 48 hour tests, were 32.3 to 36.5°C (90.1-97.7°F). The lower 48 hour TL_m was 30°C (86°F) for fish acclimated at 20°C (68°F). Striped bass occur in wide ranges of temperatures in the estuary (Talbot, 1966). They will spawn between 14.4°C (58°F) and 21.1°C (70°F). Ranges of temperature tolerated are 6.0-7.5°C (42.8-45.5°F) to 25-27°C (77-80°F). Temperature tolerances of three marine fishes have been determined by Hoff and Westman (1966). The common silverside (*Menidia menidia*) acclimated at temperatures ranging from 7-28°C (44.6-82.4°F) had an upper 48 hour TL_m range of 22.5 to 32.5°C (72.3-90.3°F) and a lower range of 1.5 to 8.7°C (34.8-47.8°F). Winter flounder (*Pseudo pleuronectes*) acclimated at temperatures of 21-28°C (69.8-82.4°F) had a lower 48 hour TL_m range of 1.0-5.4°C (33.8-41.6°F). Flounder acclimated at temperatures from 7-28°C (44.6-82.4°F) had an upper range of 22-29°C (71.6-84.2°F). Northern swellfish (*Spheroides maculatus*) were acclimated at temperatures of 14-28°C (57.2-82.4°F) and had a lower 48 hour TL_m of 8.4-13°C (47.1-55.4°F). Fish acclimated at temperatures of 10-28°C (50-82.4°F) had TL_m's of 28.2-33.0°C (82.9-90.4°F). Temperature ranges for adults are listed in Table 7.

Table 7 - Temperature ranges reported for adult marine and anadromous fish.

Species	Acclimation Temp. (C)	Lower Lethal Temp. (C)	Upper Lethal Temp. (C)	Remarks	Source
Clupea harengus		- 1.0	19.5-21.2		Brawn, 1960
Fundulus parvipinnis	14-28		32.3-36.5	48 hr TL_m	Doudoroff, 1942b
"	20	30		" " "	" "
Roccus saxatilis		6.0-7.5	25-27	Tolerated in Estuary	Talbot, 1966
Menidia menidia	7-28	1.5-8.7	22.5-32.5	48 hr TL_m	Hoff & Westman, 1966
Pseudo pleuronectes	21-28	1.0-5.4		48 hr TL_m	"
	7-28		22-29	" " "	"
Spheroides maculatus	14-28	8.4-13		" " "	"
	10-28		28.2-33.0	" " "	"
Adult Salmon		0.0	26.7	Survival Temp.	Anon., 1966

In a statement about the observed presence or absence of fish in heated areas, Trembley (1960) reported that fish may be eliminated from heated zones during warm months, but may congregate in heated areas during winter months.

ANADROMOUS FISHES

Anadromous fish are unique in their life histories. Eggs incubate in fresh water and the resulting young spend a period of a few months to several years in fresh water, then migrate to saltwater, where they grow into adults. As adults the fish mature in salt water and return to fresh water to spawn. During their life cycle, anadromous fish are subjected to various stresses such as salinity (osmotic) change, physical change, predators, and temperature (Brett, 1957).

Eggs

Investigations have shown that thermal requirements in the very early stages are more exacting than in the adult (Brett, 1956). Eggs of the sea lamprey (*Petromyzon marinus*) require the most exacting thermal levels (McCauley, 1963). The range of constant temperatures necessary for successful hatching is narrow, being 15-25°C (59-77°F). The range could be extended to 12-26°C (53.6-78.8°F) if the eggs were able to develop to the head stage before they were subjected to increased temperatures. Similar results were noted by Piavis (1961) who reared sea lamprey eggs at low constant temperatures and was unable to grow viable burrowing larvae at any temperature below 15.6°C (60°F) or above 21.1°C (70°F). Constant temperatures were used in the incubation of chinook and sockeye salmon eggs (*Oncorhynchus tshawytscha* and *O. nerka*) (Combs, 1965). Chinook salmon eggs which had developed to the 128 cell stage could tolerate 1.7°C (35°F) water for the remainder of the incubation period. Sockeye salmon eggs were less resistant to high temperatures and more resistant to cold temperatures. Their lower threshold temperatures for normal development were 4.4-5.8°C (40-42.5°F) and upper threshold temperatures were 12.8-14.2°C (55-57.5°F). A lower threshold for chinook eggs was established at 5.8°C (42.5°F) and an upper threshold at 14.2°C (57.5°F), (Combs and Burrows, 1957). Mortalities occurred when eggs were incubated above or below these temperatures.

Hayes, in 1949, subjected salmonid eggs to extreme temperatures and noted that certain tissues will exhibit cell multiplication without differentiation. Salmon embryos were incubated by Hayes, Pelluet and Gorhan (1953) in temperatures within the limits for survival. Hatching of the embryos tended to appear precociously at low temperatures.

According to Johnson and Brice (1953) reservoir water could be used for incubation when the daily mean temperatures were below 12.2°C (54°F). Chinook eggs incubated over 15.6°C (60°F) suffered excessive mortality. Results from laboratory tests conducted by Olson and Foster (1957) and Nakatani and Foster (1966) were slightly higher. They reported that chinook eggs, especially in cold water, could begin incubation at temperatures as high as 16.1°C (61°F), without significant loss. Seymour (1956) reported that young chinook eggs should be reared at temperatures ranging from 9.4°C to 14.4°C (49 to 58°F) for best results. Abnormal fry and the hatching period were increased by higher and lower temperatures. A slightly wider range of temperatures 5.6-14.4°C (42-58°F) was suggested by Leitritz (1962). As a general range for all Pacific salmon eggs LT_{50}'s were reported at 2.5°C (36.5°F) and 16.0°C (60.8°F) but less than normal survival was noted below 5.8°C (42.5°F) and above 12.8°C (55°F), (Anon, 1966).

In the natural environment, McNeil (1966) studied the effect of low temperatures in the spawning beds of pink (O. gorbuscha) and chum (O. keta) salmon and determined that freezing was important only when the maximum day-time temperatures remained below 0°C (32°F) for at least two days. Eggs and larvae of pinks and chum are able to survive at low temperatures and high salinities (Rockwell, 1956).

In a summary of the significance of temperatures on salmon egg incubation (Anon, 1966) the following points were emphasized; a) the effects of temperature vary with many things including species and race, b) mortality attributable to temperature is also a function of duration of exposure, c) temperature during the initial incubation period is critical and, d) if the initial incubation temperatures are below 5.6°C (42°F) or above 12.8°C (55°F) less than normal survival can be expected. Temperature ranges reported for the hatching of eggs are tabulated in Table 5.

Young

Young of anadromous fish, especially salmon, spend much of their life in fresh-water and most research on them pertains to this environment. Determination of tolerance limits for different species of fish may be very difficult and time consuming. Brett (1960) has reported the ultimate upper lethal levels can differ between species by as much as 17°C (31°F).

Five species of Pacific Coast salmon were tested by Brett (1952) for their temperature tolerances. The five species of salmon tested were spring or chinook (Oncorhynchus tschawytscha), silver (O. kisutch), pink (O. gorbuscha), sockeye (O. nerka) and chum (O. keta). Fish used in the tests were less than one year of age with an average length of 405 centimeters and an average weight of 1 gram. The maximum acclimation temperature was 24°C (75.2°F). Springs were reported to be very active and good feeders at 24°C (75.2°F) but growth was poor. Pinks, sockeyes, chum and cohos were all intolerant to 24°C (75.2°F) water. Of the species tested, springs and cohos were most tolerant to prolonged high temperatures, sockeyes intermediate, and pink and chum least tolerant. The upper lethal temperatures were as follows: spring - 25.1°C (77.2°F); coho - 25.0°C (77.0°F); sockeye - 24.4°C (76.0°F); pink - 23.9°C (75.0°F); and chum - 23.8°C (74.8°F). Acclimation temperatures for all species were 10-20°C (50-68°F). The lower lethal temperatures for the highest acclimation of 23°C (73.4°F) were spring, 7.4°C (45.4°F); coho, 6.4°C (43.5°F); sockeye, 6.7°C (44.0°F); and chum, 7.3°C (45.1°F). For all species the region of greatest preference was 12-14°C

(53.6-57.2°F), (Table 6). In a report on the Columbia River salmon (Anon., 1956) lethal tolerances for 50 percent of the juveniles tested were listed as 0.0°C (32.0°F) and 25.1°C (77.2°F). However, poor growth was reported for temperatures below 4.4°C (40°F) and above 18.3°C (65°F). In contrast with the above results Kerr (1953) tested young chinook salmon and reported a maximum temperature of 26.7°C (80°F) tolerated by them. He also reported them able to tolerate a rise in temperature of 9°C (16°F) in the cooling water from a steam generated electric plant.

Burrows (1963) suggests that a range in temperature for maximum producitivity in fingerlings should be between 10-15.6°C (50-60°F). His research indicated that to attain maximum productivity the water temperature must not only remain within the tolerance level of the fingerling but in species with more than a minimum stay in fresh-water, the temperature must reach that necessary for optimum growth level as well.

Tests designed to reveal the effects of temperature on the physiology of young salmon showed internal temperatures of smolts reached equilibrium with the external environment in 3-5 minutes (Harvey, 1964). Effects of temperature on fin ray and vertebrate counts were checked by Seymour (1959) who noted that the average number of vertebrae per lot of fish was less for lots reared at temperatures in the middle portion of the 3.9-16.7°C (39°F-62°F) range than for lots reared at either extreme of the range.

Several researchers have checked the effects of temperature on swimming speed and metabolism. Optimum cruising speeds occurred at 15°C (59°F) for young sockeye and 20°C (68°F) for young coho (Brett, Hollands and Alderdice, 1958). When young sockeye salmon swimming at a speed of 1 foot per second were subjected to a temperature change of 10-15°C (18°F to 27°F) their metabolic rate increased by more than 50 percent (Anon., 1962).

Migration of young fish from fresh-water to saltwater may subject them to wide ranges of temperature. Effects of temperature on pink salmon (*O. gorbuscha*) were studied by Sheridan (1960 and 1961). He reported an interaction between air temperature and snow that may cause fry to migrate to sea at unfavorable times. There is presumably one "best" time for fry to enter saltwater and the normal time of seaward migration may be best for food supplies and saltwater temperatures or other unknown factors. In addition to the temperature and stream flow in the river, the temperature and salinity of the marine environment during early life are also very important (Vernon, 1958).

During their stay in fresh-water young fish are subjected to diseases that may or may not be influenced by temperature. Both the literature and research show the effects of some diseases are increased by temperature increases. There is one disease, however, that may be reduced by increased temperature (Ordal and Pacha, 1963). The myxobacterium *Cytophaga psychrophila* is a disease of salmon fingerlings in low temperature water. Losses due to this disease can be reduced by increasing temperatures above 6.1°C (43°F) in the spring. Water temperature remaining relatively stable either above or below the optimum range for extended periods is conducive to disease development which may result in reduction of fingerlings produced (Burrows, 1963).

Adults

Adult anadromous fishes spend most of their life cycle in the marine area and enter fresh-water only to migrate up a stream to spawn. During their migration salmon do not take in food after reaching the estuary and heading upstream. High water temperatures increase their metabolic rate and may result in fuel depletion before the fish can spawn (Anon., 1962). Temperature was listed as one of the factors affecting timing of spawning runs of pink salmon (*O. gorbuscha*) studied by Sheridan (1960). For pinks, a stream temperature near 10°C (50°F) seemed to be best. Adult salmon have been reported to survive 0.0°C (32.0°F) to 26.7°C (80°F) but spawning effectiveness may be reduced below 7.2°C (45°F) and above 15.6°C (60°F) (Anon., 1966), (Table 7).

The migration of fish has been hampered by unfavorable temperatures. Brett (1957) noticed the curtailment of the migration of sockeye salmon through lakes in the spring and Major and Mighell (1966) concluded that rising or stable temperatures above 21.1°C (70°F) tended to block the entry of migrating fish from the Columbia River to the Okanogan River. A study, by Massmann (1957), of the relationship of water temperature and shad catches in the York River for a three year period showed that greatest catches-per-unit effort were made at water temperatures of 7.2°C (45°F) to 15°C (59°F). Below a water temperature of 4.4°C (40°F) the fish stopped migrating and no catches were made. The death of migrating Atlantic salmon (Salmo salar) in Nova Scotia, due to low water and high temperatures was recorded by Huntsman (1942). Fresh run grilse died at about 29.5°C (85.1°F) and acclimated grilse at about 30.5°C (86.8°F).

As noted earlier with juvenile salmon, temperature increases usually result in an increase in disease which lowers the surviving numbers of spawning fish.

Summary

Temperature fluctuations affect the metabolism, reproduction, distribution, ecology and tolerance of fishes. The effect of a fluctuation depends on the species of fish, the stage in the life history of the fish, the rate of decrease or increase in temperature and the amount of thermal fluctuation. In the marine environment temperature changes are most important in enclosed areas such as the estuaries and bays as opposed to open areas. Tolerance to temperature fluctuations is least in marine forms and greatest in estuarine and fresh-water forms.

Pelagic forms are most susceptible to temperature fluctuations since they are dependent upon water currents for much of their movement. Adult fish are usually able to select their preferred temperature gradient unless trapped in shallow or enclosed areas or forced to migrate through heated or chilled areas. Most fish have restricted ranges of temperature within which they can reproduce successfully. Larval development also requires narrow ranges of temperature. For these reasons a fish population may exist in a heated area only by continued recruitment from the outside. In such areas fish may be absent during warm summer months and present in cold winter months. In some areas populations of widely tolerant species may replace stenothermal species.

Increasing temperatures may block the migrations of anadromous fish and increase the effects of diseases on those fish. However, there are reports of temperature increases reducing losses of young salmon from disease and increasing survival of eggs.

Cold is as important to fish populations as heat because of the inability of fish to acclimate quickly to rapid decreases in temperature. Thus, in some areas fish populations may be limited by decreases as well as increases in temperature.

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V. AQUATIC PLANTS AND BENTHOS

General

Temperature regulates molecular movement and thus largely determines the rate of chemical reactions and consequently the rate of metabolism and activity of all organisms, both those with a relative constant temperature (homoeothermus) and those with a variable temperature that is identical with, or close to, their environment (poikilothermus). Because of its regulative capacity in determining the rate of metabolism, temperature presumably is the most important single environmental entity concerning life and life processes.

Variations in temperature of streams, lakes, estuaries, and oceans are normal events that result from climatic and geologic phenomena. The range of temperatures in waters that support some form of aquatic life other than viruses or bacteria is from -3°C (26.6°F) in super-cooled sea water to 85°C (185°F) in fresh-water thermal springs; most aquatic poikilotherms, if not all, tolerate only those temperature changes that occur within a much narrower range whether it be high, intermediate, or low on this scale of temperatures.

Within the same species the biological effects of a given temperature or temperature pattern may be different in different populations, at different ages, in different life cycle stages, or in the two sexes (Sprague, 1963), and such effects may depend on the temperature history of the individual tested (Prosser, et al., 1952), as well as on present or past effects of other environmental factors. Many organisms experience temperature changes in their natural habitat, and these changes can be an important prerequisite for their well being and completion of their life cycles. A constant temperature of 20°C (68°F), temperatures fluctuating rapidly and irregularly between 15° and 25°C (59 and 77°F) with an average value of 20°C (68°F), and temperatures fluctuating gradually and periodically between 15° and 25°C (59° and 77°F) with an average of 20°C (68°F) do not necessarily have the same biological effects. Thus, even if other prerequisites are satisfactory, the absolute temperature values of a body of water are only one measure of its suitability for a normal assemblage of aquatic life; consideration also must be given to temperature patterns or dynamics. For example, distinctions must be made between constant and fluctuating temperatures, between gradients, ranges, averages, frequency and intensity of changes, duration of a given pattern, and total summation (Kinne, 1963).

The temperature range tolerated by many species of organisms is narrow during very early development, then increases somewhat and finally decreases again in the "old adult." Similarly, it often is more restricted during the sexual phase than during other phases. Upper lethal temperatures may be lower for animals from cold water than for closely related species from warm water (Prosser and Brown, 1961). A similar aspect presumably could be found among closely related algae as well as other plants. Many mobile organisms such as fish, some zooplankton, certain algae, and bottom-associated animals can avoid critical temperatures by vertical and horizontal migration into more suitable conditions. Other such organisms may be attracted to areas with critical temperatures and succumb when these are attained.

Fresh-Water Algae and Other Aquatic Plants

Except for fresh waters in tropical areas, relatively broad temperature ranges naturally occur seasonally and diurnally, but even in tropical waters there may be some narrow seasonal changes or major changes resulting from unusual climatic events. Although tropical waters usually experience only minor temperature changes, significant qualitative and quantitative modifications occur in their associated flora. Similar changes have been found during summer in temperate and north-temperate fresh water apparently with no attendant temperature variation, and such phenomena have led to the hypothesis that temperature, per se, bears no relationship to floristic changes in these and other waters (Blum, 1953; Pearsall, 1923; and Butcher, 1924). Nevertheless, more recent studies employing laboratory procedures wherein variables other than temperature were static have shown that temperature, per se, does have a profound influence on aquatic algae and other plants (Phinney and McIntyre, 1965; Owens and Maris, 1964), and many others provide nonlaboratory data that strongly implicate temperature as one of the causes of both qualitative and quantitative changes in aquatic flora (for example: Cairns, 1956; Wallace, 1955; Trembley, 1960; Palmer, 1965; and Patrick, 1948). Extracellular algal products, nutrients, or other factors can cause algal population changes (Mackenthun, et al., 1964; Mackenthun, 1965; Hartman, 1960; and Fogg, 1962), and these may have been responsible for those population changes mentioned above where there were no attendant temperature variations.

Algae and other plants, like poikilothermous animals, lack physiological mechanisms to maintain constant internal temperatures, and have tissue temperatures identical with or very close to that of their environment. Terrestrial plants are subjected to much wider temperature ranges than those living in aquatic environments, but a few species of aquatic algae tolerate temperatures higher than any terrestrial plants. For example, several authors have reported that some species of algae can tolerate water temperatures as high as 85°C (175°F) as found in thermal springs (Mann and Schlicting, 1967; and Kinne, 1963), but optimal temperatures for the same or similar species may range from 51° to 56°C (123.8° to 132°F) according to Brock and Brock, 1966. Other algae, notably certain diatoms, can tolerate low temperatures near 0°C (32°F), and some may remain viable after freezing. *Ulothrix zonata*, a filamentous green algae, grows best below 15°C (59°F), and can produce reproductive bodies, zoospores, at temperatures near 0°C (32°F) in ice water (Oltmanns, 1922-23, as cited by Blum, 1953).

Such tolerances to high or low temperature extremes are not universal among algae and other aquatic plants; similarly, an individual plant may not thrive at all temperatures between those extremes mentioned above. Rather, there appears to be particular temperature ranges that are tolerated by each species and by closely related species or groups of species. A similar concept applies to optimum temperatures for aquatic algae. Thus, Cairns (1956) indicated that in an unpolluted stream diatoms grow best at 18° to 20°C (64.4 to 68°F); green algae at 30°C (86° to 95°F); and blue-green algae at 35° to 40°C (95 to 104°F). If environmental temperatures near 10°C (50°F) are increased either naturally or artificially to about 38° (100.4°F), the predominance of groups of species changes correspondingly from diatoms to green algae and finally at the uppermost temperatures to blue-green algae (Wallace, 1955). A few of the more high-temperature-tolerant species belonging to algal groups other than the blue-green may persist with the predominant blue-green species in such cases, and several less tolerant species of blue-greens may succumb with the diatoms and green algae at these higher temperatures.

Bottom Organisms

In a study by Strangenberg and Pawlaczyk (1961) on the effect of warm-water discharges on a river they found that river-bottom plants and animals decreased in number when the water temperature exceeded 30°C (86°F). The macro-invertebrate riffle fauna of the Delaware River was adversely affected by heated water effluents. The macro-invertebrate biomass was reduced from 1.04 to 0.09 grams per square foot throughout the summer in the area of maximumly heated water, as compared with a control station. A 35°C (95°F) water temperature at the time of sampling was found to be causing a detrimental effect on many organisms, especially the caddisfly, *Hydropsyche* sp., many of which were dead, while those alive were extremely sluggish. The data suggest that there is a tolerance limit close to 32.2°C (90°F) for a variety of different kinds of animals in the population structure of benthos with extensive losses in numbers and diversity of organisms accompanying further temperature increase (Coutant, 1962).

Another classic demonstration on the effects of increasing water temperatures upon the change in the composition of a macro-invertebrate population is presented by Walshe (1948). The thermal index (22-hour LD_{50}) of seven species of midge larvae reflect the probable sequence of preferred temperatures. These seven species and their thermal indices are as follows: *Tanytarsus brunnipes*, 29°C (84.2°F); *Prodiamesa olivacea*, 30°C (86°F); *Anatopynia nebulosa*, 30.4°C (95°F); *C. longistylus*, 35°C (95.9°F); and *Anatopynia varia*, 38°C (101.8°F).

In studies on the shift of the composition of macro-invertebrate populations (Wurtz and Renn, 1965), it was shown that no immediate kills resulted from thermal shock of 14°C (25°F). However, persistent exposure to 35°C (95°F) over 24 hours brought about changes in the composition of the macro-invertebrate population.

Studies of particular species of macro-invertebrates have shown that lethal temperatures vary considerably with the type of organism. Noland and Reichel (1943) in studying the fresh-water snail (Lymnaea stenalis) found that cultures died when the water temperature reached 30.5°C (89.6°F). Fresh-water snails (Viviparus malleatus) died when held at a temperature of 37.5°C (99.5°F) (Hutchinson, 1947).

The highest 24-hour median tolerance limit lethal temperatures that could be obtained by raising acclimation temperatures from 10°C (50°F) to 20°C (68°F) were estimated to be 34.6°C (94.2°F) for the sowbugs Asellus intermedius, Forks, and the scud, Gammarus fasciatus, Say, 33.2°C (91.8°F) for the scud, Hyallella azteca (Saussure), and 29.6°C (85.3°F) for the scud, Gammarus pseudolimnaeus Bousfield (Sprague, 1963).

The fresh-water snail (Physa gyrina) has been found to live and reproduce in a waste water ditch between 28° and 35°C (82.4° to 95°F) (Agersborg, 1932).

Many marine bottom-associated organisms have stenothermal or narrow temperature ranges. In some cases, a particular species may be stenothermal for one developmental stage, and eurythermal for another. Breeding or spawning requirements are generally stenothermal. The time of spawning for molluscs is highly dependent upon temperature. Most molluscs with specific temperature-breeding relationships are spring and summer spawners, and many do not spawn until a certain temperature is reached (Allen, 1963). Spawning of the American oyster (Crassostrea virginica) takes place between 15 and 32 to 34°C (59 and 89.6 to 93.2°F), depending on condition of the oyster, and the spawning process is usually triggered by a rise in temperature (Galtsoff, 1964).

A large number of species are able to tolerate higher temperatures than those at which they can breed. For example, Carcinus maenas thrives, but does not breed in 14-28°C temperatures (57.2-82.4°F) (Naylor, 1965). In the case of the European lobster, temperature controls a different part of reproduction. Larvae require a minimum temperature of 15°C (59°F) even though the developing eggs, and adults, will tolerate lower temperatures (Gunter, 1957). For the above two cases, temperature limits the populations and recruitment of organisms must occur from outside the heated area.

Physiology, metabolism, and development are all affected by temperature. At a temperature of 6-7°C (42.8-44.6°F), C. virginica ceases feeding. Above 32°C (89.6°F) ciliary action, responsible for movement of water, rapidly decreases; and almost all functions of the body cease, or are reduced to a minimum at 42.0°C (107.6°F). The European oyster, Ostrea lurida, has a tendency to close it's shell in response to falling temperatures. At 4-6°C (39.2-42.8°F) the shells of oysters remain closed most of the time; at 6-8°C (42.8-46.4°F) the shells open for about 6 hours per day; and at 15°C (59°F) the shells remain open for 23 hours per day (Galtsoff, 1964). Very little is known about prolonged effects of temperature above 32-34°C (90-94°F) on oyster populations. Long, continued exposure to high temperatures may impede the normal rate of water transport. When either low or high temperatures cause a closing of shells or a ceasing of ciliary action, oysters cease to feed and lose weight. Thus, temperature may produce an effect similar to chronic toxicity.

Acclimation and tolerance of bottom-associated organisms may be affected by temperature changes. The crab (Hemigrapsus nudus) can regain tolerance to high temperatures, after a low temperature history, in less than a week. Shore crabs (Pachygrapsus crassipes) may require a half time of six days in order to acclimate to a temperature change of 7.5°C (13.5°F) (Kinne, 1967). The giant scallop (Placopecten magellanicus) acclimates rapidly to a rise in temperature of 1.7°C (3.1°F) per day, but may take as long as three months to lose this acclimation to high temperatures (Dickie, 1958). The opossum shrimp (Neomysis americana) is very intolerant to temperature increases, and does not appear to survive at temperatures above 31°C (87.8°F) in the Chesapeake estuary (Mihursky and Kennedy, 1967).

Distribution of benthic organisms may be controlled by temperature. Reef-forming corals will not live where temperature falls below 18-19°C (64.4-66.2°F). The American oyster (C. virginica) on the Gulf coast is present in water that may vary from 4-34°C (39.2-93.2°F); while the European oyster (O. edulis) is restricted to water with temperatures of 0-20°C (32-68°F) (Gunter, 1957). In a study on the York River, in Virginia, Warinner and Brehmer, 1966, found that the community composition and abundance of marine benthic invertebrates in the river were affected by thermal discharge over a distance of 300-400 meters from the discharge outfall. They concluded that during the months of high normal river temperatures there was clear evidence of biological stress.

Cold is as important as heat in its effects on marine organisms. Cold water may kill directly, or in some cases indirectly when organisms are "numbed" or rendered inactive and unable to protect themselves from predators (Gunter, 1957).

One of the benefits derived from heated water is the defouling of intake pipes. Experiments have shown that fouling by Mytilus edulis and M. californianus could be controlled by tri-weekly reversals of heated discharge water either for periods of one hour at 38-41°C (100.4-105.8°F) or for seven hours at 34.5°C (91.4°F) (Naylor, 1965).

Summary

1. Temperature is one of the most important single environmental entities concerning life and life processes. The various functions of an organism may have somewhat different temperature ranges, and if these are not provided in the habitat the organism will die.

2. When water temperatures are increased, the predominance of groups of algal species changes correspondingly from diatom to green algae and finally at higher temperatures to blue-green algae.

3. The number and distribution of bottom organisms decrease as water temperatures increase with a tolerance limit close to 90°F for a "balanced population structure. Studies of particular species of macro-invertebrates have shown that lethal temperatures vary considerably with the type of organism. In some cases a particular species may be stenothermal for one developmental stage, and eurythermal for another. Thus, a large number of species are able to tolerate higher temperatures than those at which they can breed.

4. Cold is as important to aquatic plants and benthos as is heat.

5. One of the beneficial uses of heated effluents is the defouling of intake pipes; accomplished by reversing the flow of water through the pipes for a specified period of time.

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